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THE MORECS DISCUSSION MEETING
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Edited by

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ABSTRACT

A report of a meeting held at IH in April 1981 to discuss the Meteorological Office Rainfall and Evaporation Calculation Scheme, MORECS. The main emphasis was on the estimation of soil moisture deficits. The papers include a description of MORECS, discussions of some of the assumptions included in MORECS, a comparison of MORECS's estimates of soil moisture deficit with field measurements, and reviews of the scheme and its use in the agriculture and water industries.

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PREFACE

The Meteorological Office Rainfall and Evaporation Calculation Scheme, MORECS, was introduced in 1978 to provide a service to the agriculture and water industries which both require real-time soil moisture deficit information. Estimates of actual evaporation, hydrologically effective rainfall and soil moisture deficit are published weekly in the MORECS bulletins.

In 1979 the Institute of Hydrology began a project to evaluate the accuracy of deficit estimates prepared by MORECS. The preliminary findings of this project concurred with reports from MORECS users that the system did not always estimate soil moisture deficits successfully. The MORECS Discussion Meeting was arranged to provide a forum for discussion by MORECS users of their experience with the system, their requirements of it and possible improvements. The meeting took place on 10 April 1981 at the Institute.

We are very grateful for the cooperation of the Meteorological Office regarding the meeting and for the involvement of Bracknell staff, especially Dr N Thompson. Dr R N Crossett acted as Chairman. Professor J L Monteith and Mr K F Clarke agreed to provide overviews of MORECS in the contexts of agriculture and hydrology respectively. The presence of Dr H L Penman was keenly felt as ideas for which he was originally responsible were discussed again. Finally, thanks are also due to those staff at the Institute who assisted in the organisation of the meeting.

C M K Gardner

June 1981

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1 MORECS

Dr N Thompson, Agriculture Section, Meteorological Office

MORECS is an acronym for the Meteorological Office Rainfall and Evaporation Calculation Scheme introduced about 3 years ago as an eventual replacement for the Estimated Soil Moisture Deficit (ESMD) bulletins which were first issued by the Office about 15 years earlier. The main differences between the two systems are summarised in Table 1. The most important differences are that MORECS uses a more fundamental method of estimating potential evapotranspiration (PE), and employs a rather better method for modifying the PE estimates in the light of current soil moisture deficits (SMDs) in order to estimate actual evapotranspiration (AE)*. In summary, MORECS attempts to be more precise, more fundamental and more comprehensive than ESMD, and is issued more frequently.

TABLE 1 MAJOR DIFFERENCES BETWEEN MORECS AND ESMD

	MORECS	ESMD
Frequency of issue	Weekly	Fortnightly
Form of output	Grid-square average	Isopleths (drawn manually)
Method	Modified Penman-Monteith	"Climatological" Penman, modified by sunshine
Number of crops/surfaces	∿ 10	3
Soil water availability	High	Medium (for main outputs)

MORECS since its introduction has suffered a series of modifications which have been the result of input by a number of people. In fact there have been enough people involved with it to suggest likening it to a meteorological camel; the camel being an animal which, we are told, was probably designed by a committee! The purpose of this paper is to describe in broad detail not the anthropology but rather the anatomy of MORECS, and in particular to point to those areas where there are, or have been deficiencies, and to review very briefly the substantial changes which have just been completed and which become operational in May 1981.

The main components of MORECS

The present system has five main components (Table 2). In the first the values of meteorological variables which are sometimes called the Penman variables (sunshine, temperature, vapour pressure, wind speed and rainfall) are extracted daily from the Synoptic Data Bank at Bracknell, and from these are obtained grid-square values by interpolation, and finally weekly averages on the day of issue of MORECS: each grid-square is 40 x 40 km. Estimates of weekly PE are then made from the weekly-averaged inputs, from which the PE's are estimated each day by a

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* *'Evapotranspiration' is a clumsy word, and 'evaporation' will be used in the remainder of this account, with a qualification when the reference is to evaporation of surface moisture from crops or bare soil.*

TABLE 2 THE COMPONENTS OF MORECS

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1. Data collection, interpolation and averaging
2. Data analysis to obtain evaporative demand over each grid square
3. Conversion of evaporative demand to actual evaporation using a soil moisture extraction model
4. Calculation of water balance and excess rainfall
5. Data output

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sunshine-correction method. At present a modified form of the Penman-Monteith equation is used for these calculations, but earlier versions of MORECS used another modified form proposed by Thom and Oliver in 1977. The basic surface type which is considered is grassland, but there is some attempt to include in a less rigorous sense other surfaces ranging from bare soil to forest. The estimates of available energy which are required for these calculations are made by Penman's method, with empirical modification to provide a better estimate of longwave radiation. An allowance is now made for the soil heat flux, based on an annual average cycle of soil warming and cooling. In the third part of MORECS the PE estimates are converted to estimates of actual evaporation, by progressively reducing the rate of water loss from the potential value to zero as the available soil moisture decreases from 60% of its maximum value to zero. These calculations are now made for soils of high water availability only. The next part calculates the water balance under the various types of cropped surfaces, and also under the average land use for each square, in this latter case using the relative proportions of the various surfaces in each grid square. The final stage is the production of computer-drawn maps showing the grid-square weekly averages of the Penman variables, and also PE, AE, SMD and excess rainfall for grass and real land use. Printouts are also produced showing evaporation and SMD for the individual surface types. Distribution of output is usually by post, but there are limited issues by Telex, facsimile and Prestel.

The meteorological data inputs and their interpretation

The meteorological data inputs are obtained each day from about 125 synoptic stations which measure some or all of the Penman variables. The stations are distributed widely over Great Britain but a large number are near the coast or in low-lying areas, and there is a very poor coverage of the upland regions (Figure 1.1). Over England and Wales about half the MORECS squares are without a synoptic station, but in Northern Scotland the position is far worse, with very few away from the coasts. Obviously there are considerable difficulties in estimating representative grid-square values for the Penman variables. The method adopted is to use objective interpolation from either daily or weekly average station values. A computer search is made for the 9 nearest stations within 100 km of each grid-square centre. The 6 nearest of these are selected, with no more than 2 in each octant. Often it is not possible to find as many as 6 stations, but when there are at least 3 the required value is obtained by a plane fit.

Inverse distance weighting is used when there are less than 3 stations. Over a weekly averaging period the vapour pressure and wind speed show relatively small horizontal gradients and so the interpolation does not lead to large errors usually. The same can also be said about air temperature when the values have been reduced to mean sea-level, using an estimate of the mean lapse rate: MORECS

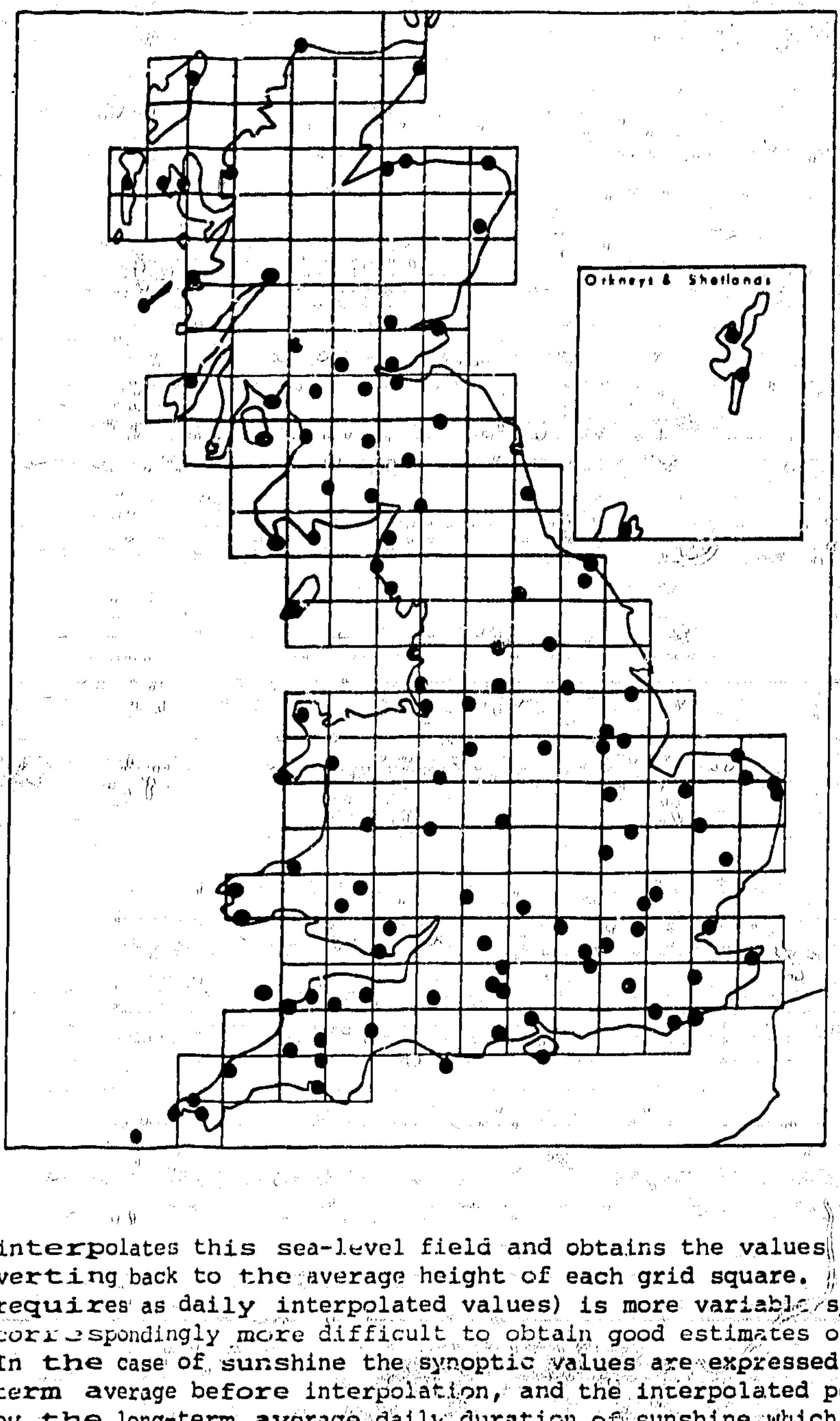

FIGURE 1.1

The MORECS grid and locations of synoptic stations

interpolates this sea-level field and obtains the values it requires by then converting back to the average height of each grid square. Sunshine (which MORECS requires as daily interpolated values) is more variable spatially, and it is correspondingly more difficult to obtain good estimates of grid-square averages. In the case of sunshine the synoptic values are expressed as a percentage of long-term average before interpolation, and the interpolated percentage is multiplied by the long-term average daily duration of sunshine which has been calculated for each grid-square from all available climatological station data. There are of course negligible numbers of sunshine stations in mountainous areas, and it is suspected that the estimates of average sunshine are too large for the grid-squares containing substantial areas of high ground.

Rainfall interpolation

Rainfall is treated in a rather similar way to sunshine, by first expressing the measured daily values as a percentage of long-term average, and then interpolating these percentages. Finally the interpolated percentage at each grid-square centre is multiplied by the long-term daily average for the whole grid-square which has been calculated from the very numerous network of climatological rainfall stations. This is an honest attempt to cope with the very large spatial variations of long-term average rainfall which occur across grid-squares which straddle widely varying topography. Unfortunately it is of less value when the rainfall is spatially inhomogeneous even over fairly uniform terrain, which is often the case in summer with convective precipitation. It is for this reason that farmers are recommended to install their own raingauge if they want best estimates of their week-to-week irrigation needs.

The interpolation errors for rainfall can sometimes be very large. Figure 1.2 shows an example for the summer of 1980 which of course included a very wet June.

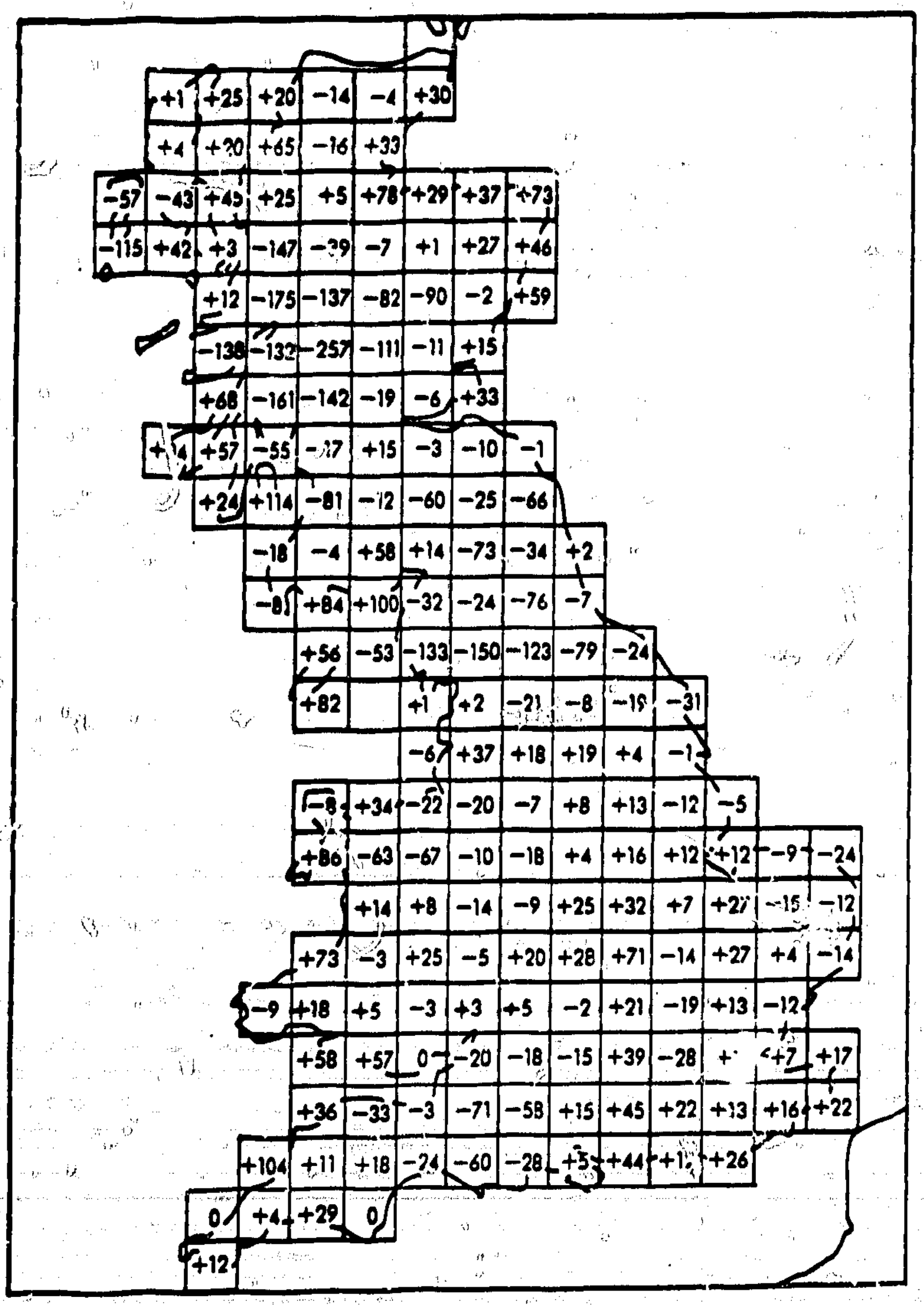

FIGURE 1.2

All station grid-square rainfall minus MORECS rainfall, June - August 1980 (mm)

Here the total rainfall for each square for this period, obtained from the daily MORECS values, has been compared with total rainfall calculated using all 6000 or so raingauges in Great Britain. Clearly there are some very large discrepancies, especially in the more hilly districts. In a drier summer the differences would have been smaller on average, but probably still significant. The effect of errors such as these on SMD's is usually less than one might expect because higher actual than estimated rainfall means that more evaporation takes place at the potential rate than calculated, and vice versa, which compensates for the errors to some extent. In spite of this the position is not satisfactory and one can but hope that one day there will be synoptic radar rainfall estimates to reinforce the raingauge values and reduce errors in areal rainfall estimates.

Most of the major errors shown in Figure 1.2 are over hilly districts, and generally result from overestimation of rainfall by MORECS. The method by which grid-square rainfall is obtained from point rainfall, outlined above, assumes that any topographic enhancement is by some fraction which is independent of season. However it is probably reasonable to assume that the fractional enhancement will be larger when winds are stronger (ie in winter) and the topographically-induced increases will be smaller when winds are light and rainfall is more convective in nature (ie in summer). It is possible then that changing the rainfall interpolation routine in MORECS so that the synoptic data are converted to percentages of monthly or seasonal, rather than annual, rainfall before interpolation would lead to better grid-square estimates. It is hoped to explore this possibility in the near future, and, if verified, to incorporate the necessary changes in MORECS.

Calculation of daily potential evaporation

Even a perfect interpolated set of grid-square values of the Penman variables provides no guarantee of perfection in the final outputs of MORECS. One of the major hurdles to be negotiated (or perhaps one should say morasses to be circumnavigated) is the accurate calculation of daily PE values for each square. Several methods which perform this operation have been used in MORECS, but they are all based on the original version of the combination equation produced by Penman in 1948:

$$E = \frac{1}{\lambda}\left(\frac{\Delta \text{ x net radiation + aerodynamic term}}{\Delta + \gamma}\right) \qquad (1)$$

where λ = latent heat of vaporisation
γ = psychrometric constant
$\Delta = \partial e/\partial T$: e = vapour pressure T = temperature

Equation 1 has a denominator which is independent of surface type, which can only be the case if the surface is thoroughly wet; this is partly compensated by the use in the equation of an aerodynamic contribution which has been shown to be an underestimate. MORECS first used a revised version of equation (1) produced by Thom and Oliver in 1977.

$$E = \frac{1}{\lambda}\left(\frac{\Delta \text{ x available energy + m x Penman's aerodynamic term}}{\Delta + \gamma(1 + n)}\right) \qquad (2)$$

They showed that m has a typical value of about 2.5. The term n in the denominator of Equation (2) is strictly a function of the physiology of the cropped surface, and also the wind speed: it varies from day-to-day but has a typical value around 1. In MORECS it was assigned a fixed value which was changed each month, but this produced substantial anomalies between adjacent squares in which the wind speeds were somewhat different. For example the PE was overestimated for squares in which the wind speed was greater than the average value implied by the value chosen for n.

The version of the combination equation used in the current MORECS is basically the Penman-Monteith

$$E = \frac{1}{\lambda}\left(\frac{\Delta \times \text{available energy} + \text{corrected aerodynamic term}}{\Delta + \gamma(1 + r_s/r_a)}\right) \qquad (3)$$

but with the aerodynamic resistance r_a written in a similar way to that proposed by Penman, with the Thom and Oliver correction to a more appropriate value for surface roughness. Thus,

$$r_a \simeq 250/(m(1 + 0.54U)) \quad (\mathrm{sm}^{-1}) \qquad (4)$$

where U is the wind speed at 2 m (in ms^{-1}). The advantage of writing the aerodynamic resistance in this way is in providing a simple way of allowing for the enhanced turbulent mixing caused by free convection on sunny days. It is possible to write an exact combination equation, but it cannot be evaluated without iteration, so is not suitable for routine calculations.

The Penman-Monteith equation requires an explicit estimate for the bulk resistance r_s of the surface from which evaporation is taking place. There is no difficulty when the surface is thoroughly wet because r_s is then zero: it is usually kept at this value until all water intercepted by the surface foliage has been calculated to evaporate. In the case of dry surfaces the literature abounds with measured values for r_s, or else measured resistances of individual leaves from which estimates of r_s can be made. What the literature does <u>not</u> abound with are values of r_s outside the temperate latitude summer, say from autumn to early spring, when even the most dedicated plant physiologist seems to remain in his laboratory with his porometer locked away until warmer weather returns. So it is not easy to specify representative values for r_s in a year-round model like MORECS. In the event the values selected for 1980, while fairly typical of expected minimum values for unstressed crops, apparently were rather smaller than averages for commercial crops, and so the estimated PE's turned out to be larger in many cases than the evidence in the field suggested that they should have been.

Before passing on to MORECS' treatment of the effects of soil moisture deficit, a brief mention of how the other important term in the combination equation, the available energy, is calculated is appropriate. Thus,

$$\text{Available energy} = R_N - G \qquad (5)$$

where

$$\begin{aligned} R_N &= \text{net shortwave} + \text{net longwave radiation} \\ &= \alpha R_a\,(a + bn/N) + \varepsilon\sigma T^4\,(-0.56 + 0.08\sqrt{e})\,(0.1 + 0.9n/N) \end{aligned} \qquad (6)$$

with

σ = Stefan's constant
α = albedo ($\sim$ 0.12 - 0.25)
R_a = solar radiation at top of atmosphere
n = measured sunshine hours
N = maximum possible sunshine hours
ε = emissivity of surface ($\sim$ 0.95)
T = surface (screen) temperature
G = flux of heat into soil

Equation (6) essentially follows the approach suggested by Penman in 1948 which uses treatments of short and longwave radiation given by Angstrom and Brunt.

The ratio of measured sunshine to the maximum possible for that week is used in an empirical expression to estimate the downward total of solar radiation, part of which is returned to space after reflection at the surface. The net longwave radiation is calculated using the MORECS temperature and vapour pressure to estimate both the sky radiation and the radiation from the surface, with the sunshine ratio used to provide a correction for enhanced sky radiation when cloud is present. A comparison with observations at several places in Britain has shown that for most months the calculated radiation exceeded the measured values, presumably because of an incorrect choice of constant values in Brunt's formula. Adjustments are made therefore to the calculated values to remove this anomaly, which incidentally is consistent with the surface temperature being higher than screen temperature during most days. Finally the soil heat flux is approximated by the climatological average heat storage in the soil.

<u>The soil moisture extraction model</u>

MORECS uses a soil moisture extraction model which has the virtue of simplicity, but also some deficiencies. Other papers describe soil moisture modelling in more detail (Gardner, p 11, Calder p 28) and so the MORECS version is outlined only briefly here. It uses the concept of field capacity which is assumed to be a unique state of a soil, reached quickly after thorough wetting and rapid drainage of excess moisture. This concept is very useful in some agricultural contexts because, once accepted, it allows soil moisture budgeting to be carried out without regard to soil properties such as hydraulic conductivity. It does also lead to some difficulties. For example deep percolation of rainfall may occur on some soils when relatively dry so that the upper layers are not necessarily restored to field capacity following rainfall. Soils with low hydraulic conductivity may show drainage for weeks following a complete wetting and obviously the idea of field capacity is less useful for these. Water may also flow upwards to replace that extracted by roots in the zone above. MORECS at present ignores all of these difficulties.

The amount of soil water available to a particular crop is the difference between that at field capacity and at permanent wilting, over the rooting zone of the crop. The model assumes that 40% of this water is extractable without causing any check in evaporation, and the remaining 60% is extracted at a linearly decreasing rate so that the actual evaporation eventually declines to zero. Any rainfall is assumed to be available to the crop at the full potential rate regardless of the moisture deficit before the rain fell. One might ask how realistic is such a model from an agricultural point of view, and the answer is probably quite good. It is known of course that, when the evaporative demand is very small, crops can extract moisture at close to potential rate up to large SMD's and equally, when the demand is large, a check in transpiration can occur at rather small SMD's, where the size of "large" and "small" depends on the soil properties to some extent. In Britain the evaporative demand is seldom very large, and when it is small there is often adequate soil moisture. So MORECS' fixed break point at 60% available soil moisture, which is consistent with field data from some soils, is probably realistic enough.

The next part of MORECS calculates the soil moisture balance from the estimated rainfall and actual evaporation: it is at this point in particular that the system is hydrologically unrealistic. The procedure uses the actual evaporation to calculate the current soil moisture deficit which is decreased by the amount of rainfall over the same period. If the SMD becomes negative as a result of this, the departure from field capacity is assumed to be hydrologically effective in the sense of aquifer recharge of sub-surface drainage. This approach neglects firstly deep percolation by which rainfall is lost to aquifers before the overlying soil is returned to field capacity, and secondly run-off which will occur at times when there is an SMD. A system like MORECS will probably never be able to provide a satisfactory treatment of deep percolation, although it might be possible to produce something applicable to an individual site rather than whole grid-squares. In the case of run-off one feels that it should be possible to give a broad estimate for an area, based for example on surface cover, soil type, the recent rainfall sequence, and the spectrum (distribution) of surface slopes. Hydrologists may disagree!

The new MORECS

This broad description of MORECS has avoided mentioning very much of the detail of the system because it would not be appropriate, or possible, to present this in a paper of reasonable length. However there are some detailed aspects which ought to be described now, but rather than doing so in isolation, they will be discussed in relation to the very substantial changes made to the system in the past few months and which will be introduced in May 1981.

At present PE is calculated from weekly-averaged data and then apportioned to each day according to the daily sunshine. The new MORECS does the full calculation each day, separately for daytime and night-time. One can argue that splitting up the day like this is usually unnecessary, but it was convenient to incorporate this change when MORECS was revised because it provides some information on night-time condensation which may have value in the future in connection with the provision of operational information on the suitability of weather for the spread of certain fungal diseases.

The current MORECS uses monthly average estimates for the surface resistance r_s, but the new version calculates r_s each day, using an assumed leaf area index for the crop where appropriate in a relation suggested by Grant in 1975:

$$\frac{1}{r_s} = \frac{a^1}{r_{soil}} + \frac{b^1}{r_c} \qquad (7)$$

where a^1 = fraction of net radiation reaching soil surface
b^1 = fraction of net radiation intercepted by crop canopy
r_c = canopy resistance of a very dense crop
(a^1 and b^1 are functions of canopy leaf area index)

Equation 7 allows automatically for less than full cover in seasonal crops by incorporating a weighted soil surface resistance in parallel with the canopy resistance (the present MORECS does separate PE calculations for soil and seasonal crops and then combines the results by linearly weighting them according to percentage crop cover). An advantage of the revised system is that r_s can be written as a function of soil moisture deficit, for example as suggested by Russell (1980), and so actual evaporation can be calculated directly.

The new MORECS produces outputs for soils of low, medium and high available water capacity; the standard issue will in future be for soils with medium available water, in contrast to the current issue which is for those with high available water capacities and has probably misled some users in the past. The choice of the particular values of soil water available to the various crops is necessarily rather arbitrary. In the case of spring-sown crops the available water increases as the rooting depth increases and account is taken of this. The selected maximum values of SMD's which can develop are given in Table 3.

TABLE 3 MAXIMUM SMDs UNDER VARIOUS CROPS (mm)

	Current MORECS (a)	New MORECS (b)
Bare Soil	∿15	20
Grass	200	125
Spring Barley	225	140*
Winter Wheat and Barley	225	140
Potatoes - early	125	90*
- maincrop	125	90*
Sugar Beet	125	140*
Deciduous Trees	500	175
Orchards	425	150
Conifers	500	175
Upland	50	50

(a) - high available water soils
(b) - medium available water soils: high = +25%
low = -25%
* - at maximum rooting depth

An interesting type of surface cover here is deciduous trees which presumably have much of the rooting system near the surface, but also some tap rooting. These trees will probably suffer a major check in transpiration when available water in the primary root zone is exhausted, but will continue to transpire at a reduced rate long beyond this point using water in the layers occupied by the much deeper roots. It may well be inappropriate to assign a maximum available soil moisture content in these circumstances. Conifers also pose a problem because they are often planted in poor soil where they survive even with very shallow roots, and yet on good soils they can increase their rooting depth and then presumably extract large quantities of water. This obviously leads to difficulties in estimating average water use in grid-squares with very variable soils and vegetation.

Conclusion

In conclusion, it has been recognised that the results produced by MORECS in the past have sometimes fallen substantially short of the ideal, and it is for this reason that major alterations have been made to the system recently. Further changes to the system are still desirable, for example to make it more realistic hydrologically by incorporating simple but effective treatments of run-off and slow drainage of the soil profile, and by improving the rainfall interpolation scheme with the help of monthly or seasonal, rather than the annual averages used to normalise the synoptic data at present. It has not been possible to give more than a very brief outline of the current MORECS. The new version of MORECS has also been mentioned only briefly but a detailed report will become available during 1981.

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2 THE SOIL MOISTURE EXTRACTION MODEL

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The MORECS system calculates daily grid square values of potential evaporation and rainfall. These values are modified to allow for the evaporation of intercepted rainfall and then used by the soil moisture extraction model to produce daily soil moisture deficit (SMD) values for several crop types in each grid square. The SMDs prepared for the Wednesday of every week are published in the MORECS bulletins. The aim of this paper is to briefly describe and comment on the soil moisture extraction model used by MORECS to represent crop water use. A summary of this component of the system has been published by Wales-Smith and Arnett (1980).

The model is based on that devised by Penman (1949) which incorporates three important features:

1 While there is an SMD all changes in soil moisture content are assumed to be due only to rainfall inputs, and evaporation and transpiration losses.

2 When the profile is wetter than field capacity excess rainfall (ie in excess of the evaporation demand) is assumed to drain; there is no allowance for surface run-off.

3 When the SMD exceeds a threshold known as the root constant by 25 mm, the subsequent transpiration rate is less than the potential rate (traditionally one twelfth of the potential rate).

The structure of the model

MORECS uses a two layer structure to represent the response of the soil to incoming rain and the demand of the plant for water. The size of the reservoir of moisture in the soil that is available to plants is known as the available water capacity. In MORECS this reservoir is conceived as being divided into two parts which are known as the TOP and BOTTOM layers. Water may pass from the TOP to the BOTTOM layer. More importantly, water in the TOP layer is readily available to the plant and maybe transpired at the potential evaporation rate. Water in the BOTTOM layer is less accessible to the plant. The rate at which the plant may use water from the BOTTOM layer depends upon how much water is present within it.

The relative capacities of the two layers are always the same. The BOTTOM layer is always 1.5 the capacity of the TOP layer which is known as MAX. Thus when both layers are full 40% of the available soil moisture is in the TOP layer and 60% in the BOTTOM layer. The TOP layer can temporarily be overfilled, ie its water content may exceed MAX (see later).

Layer	Capacity	Water Availability	
TOP	MAX (40% AWC)	Ea = Ep	Ep = potential evaporation
BOTTOM	1.5 MAX (60% AWC)	Ea < Ep	Ea = actual evaporation/ transpiration

The soil moisture content is defined as being at field capacity when the layers are full. There is a soil moisture deficit if either, or both are not full. The maximum deficit allowed is equal to the sum of the capacities of the two layers, 2.5 MAX, corresponding to the available water capacity (AWC).

The running of the model

Assuming that it is known how much water remains in each layer after the previous day's accounting, what happens to the rainfall and how is the evaporative demand satisfied on a given day ? The TOP layer is always dealt with first. When it is emptied evaporation is allowed from the BOTTOM layer:

1 The daily rainfall is added to the water content of the TOP layer. Although the layer water content may thus exceed MAX it does not initially overflow.

2 Removal of the water from the TOP layer is allowed at the potential evaporation rate.

3 If the daily potential evaporation demand, Ep, is not large enough to reduce the quantity of water in TOP layer to less than MAX, the excess water is passed to the BOTTOM layer. Should the BOTTOM layer consequently exceed its capacity (ie 1.5 MAX) the excess water is regarded as drainage.

4 However, if the TOP layer is emptied as a result of transpiration from it and Ep has still not been satisfied,transpiration is allowed from the BOTTOM layer, though at a reduced rate.

5 If the BOTTOM layer is also emptied, then no further transpiration can occur and the maximum deficit is reached.

6 The total deficit is calculated by summing the final deficits in each layer.

In the version of MORECS operative until May 1981 the relationship between actual and potential transpiration, from the bottom layer, for a cropped soil, was:

$$\frac{Ea}{Ep} = 1 - (\frac{SMD - MAX}{1.5\ MAX})$$

This has been revised and Ea will be calculated directly in future assuming surface resistance to be a function of SMD (Thompson, p 8). For bare soils a different, exponential relationship only allows very small deficits to develop. This was adapted from a model devised by Smith (1975).

$$\frac{Ea}{Ep} = 1.92\ \exp\ (-0.7\ SMD)$$

It will be apparent from this description that in MORECS, MAX values are used as critical SMD thresholds, similar to root constants. The size of MAX and so that of the total reservoir of available soil moisture (2.5 MAX), vary according to both soil type and crop. Three classes of soil are recognised according to available water capacity per metre depth of soil as follows: < 100 mm m^{-1}, 100-180 mm m^{-1} and > 180 m^{-1}. Generally the AWCs of coarse textured soils (sands and gravels) are less than 100 mm m^{-1}, while those of fine textured soils with a good pore structure are greater than 180 mm m^{-1}. The majority of soils have an AWC within the range 100 to 180 mm m^{-1}.

The table lists, for three crops, the MAX and 2.5 MAX values which are related to the AWC values as follows. Consider as an example grass growing in a soil of AWC range 100-180 mm m^{-1}. The 2.5 MAX value is then 160 mm, from the table, implying that if the AWC of a given soil is 100 mm, then the roots extract water from the top 160 mm of the soil profile. But if the AWC of the soil is higher then the depth of soil which can be exploited must be rather less.

CROP	AWC mm m^{-1}	MAX mm	2.5 MAX mm
	<100	50	125
GRASS	100 - 180	64	160
	>180	80	200
	<100	58	145
CEREALS	100 - 180	72	180
	>180	90	225
	<100	33	83
ROOT	100 - 180	40	100
CROPS	>180	50	125

A MAX value of 3 mm is used for bare soils. During the period in spring before arable crops achieve full cover, SMDs for these crops are calculated as a weighted mean of two SMD estimates. One is the SMD which would occur if the crop was at full cover and the other represents bare soil. The weighting is in accordance with the assumed percentage of crop cover.

Some limitations of the soil moisture extraction model

The MORECS soil moisture extraction model incorporates both the field capacity and the root constant concepts. Because of the reliance on the field capacity concept, according to the model, drainage may only occur if the soil profile moisture content is at or greater than field capacity, and during deficit periods the only water losses allowed from the profile are in the form of transpiration and evaporation. This is physically incorrect and for some soils significant errors could arise from this assumption.

MORECS defines the field capacity state of a soil as the soil moisture content on the date after which transpiration losses exceed the rainfall input. There is no reference to the field situation or allowance for the fact that in many soils field capacity is not a reproducible moisture content.

The only water input to the profile accounted for is rainfall and no allowance is made for surface run-off during intense rainfalls, or on steep slopes.

The two part soil moisture reservoir concept is somewhat confined by the use of the terms "TOP" and "BOTTOM" which imply superimposed layers. In fact it is more physically valid to regard the reservoir as non-layered but comprising water in pores above a certain size and therefore freely available (TOP layer), and water in smaller pores which is not so easily extractable by plants (BOTTOM layer). However an advantage of the two layer structure of the model is that it attempts to represent the situation whereby a soil with a large deficit, transpiring at a rate below potential, is rapidly wetted only at the surface as a result of rain. The model will permit the rate of transpiration temporarily to increase substantially although the total SMD may still exceed the MAX threshold, and thus it represents the field situation quite well.

MORECS discriminates to a certain extent between soils of different water holding properties through the use of three MAX values for each crop. However, the values assigned to MAX are critical in determining the success or otherwise of the system in estimating SMD. The soil factors which actually cause the rate of transpiration of a plant to fall below the potential rate are the increased soil moisture tensions and reduced hydraulic conductivity resulting from decreasing soil moisture content. Soil moisture content (or SMD) is only an index of these factors, which is site dependent, because the relationship between soil moisture tension, conductivity and moisture content varies from one soil to another. The effect of soil factors on moisture extraction is thus rather greater than the model admits.

The significance of some of these shortcomings is discussed in the following paper.

Penman, H L, 1949. The dependence of transpiration on weather and soil conditions. J. Soil Sci. 1, 74-89

Smith, L P, 1975. Methods in Agricultural Meteorology. Elsevier, Amsterdam.

Wales-Smith, B G and Arnett, J A, In press. The Evaporation Calculation System Used by MORECS. WMO Technical Note.

3 PROBLEMS ARISING FROM THE FIELD CAPACITY CONCEPT IN COMPARING MEASURED SOIL MOISTURE DEFICITS WITH MORECS PREDICTIONS

J P Bell Institute of Hydrology

The validity of the soil moisture deficit (SMD) concept depends on that of the field capacity concept. While in some field situations a reproducible field capacity exists, in many others it does not.

Field capacity is conceived of traditionally as being the water content of a profile which, after having received excess water, drains within 48 hours to a reproducible water content distribution. Thereafter, further drainage is so small that it can be neglected.

Meteorological models for predicting SMD such as MORECS depend on the validity of field capacity because they take account only of inputs and outputs of water at the soil surface once the integrated profile water content is at or below field capacity. No provision is normally made for further drainage nor for upward fluxes across the base of the profile. Furthermore, the depth of the profile is implicitly conceived as being of constant, but undefined, depth. The question arises however, to what extent is the acceptance of the field capacity concept valid:

(a) for defining measured soil moisture deficits?
(b) *for defining MORECS deficits?*

At this point it is helpful to examine the physical basis for the concept.

A reproducible field capacity condition can generally be established in two situations:

(1) The first is in soils in which conductivity is provided principally by a macropore system, the matrix being very poorly conductive. A structured clay is the best example of this. As the soil drains via the macropores the potentials fall and the macropores are emptied progressively. Conductivity decreases rapidly and, at a certain threshold value of moisture content and potential (which is dependent on the soil), macropore conductivity ceases and further movement is controlled by the very much lower conductivity of the clay matrix. Taking a conductivity of 0.1 mm/day as "negligible", this might typically correspond to a matric potential of 100 cm water head (0.1 bars) (Fig. 3.1).

Thus, in the potential profile diagram (Fig. 3.2) a matric potential field can be defined (the shaded area) and potential profiles lower than this will produce negligible drainage.

Profile (a) represents a draining profile which quickly moves towards (b), which corresponds to the stage at which conductivity has fallen to the negligible value. Thus, profile (b) represents "field capacity" and the corresponding water content profile (b) in Fig. 3.3 may be considered to be reasonably reproducible and to represent field capacity for practical purposes. A subsequent change in the level of the water table would have little effect on the water content of the upper profile. The only problem here is that significant drainage may persist for longer than the traditional 48 hours.

(2) The second situation where a reproducible field capacity state exists is at the opposite extreme, in much more conductive soils. Here, the higher conduc-

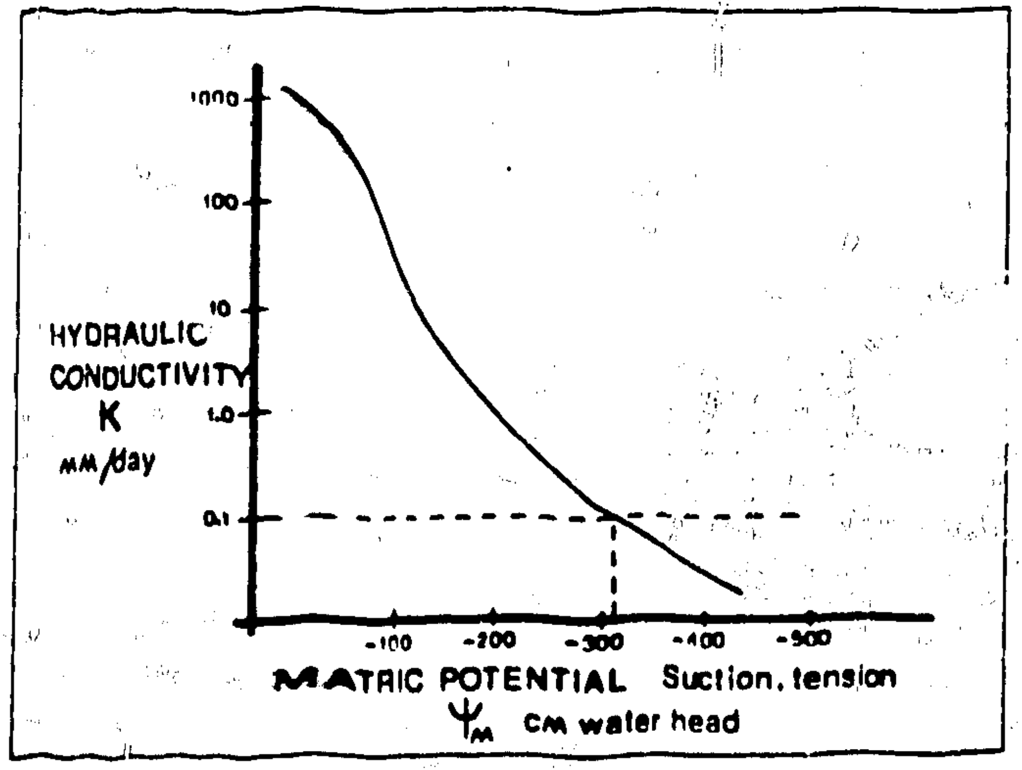


FIGURE 3.1

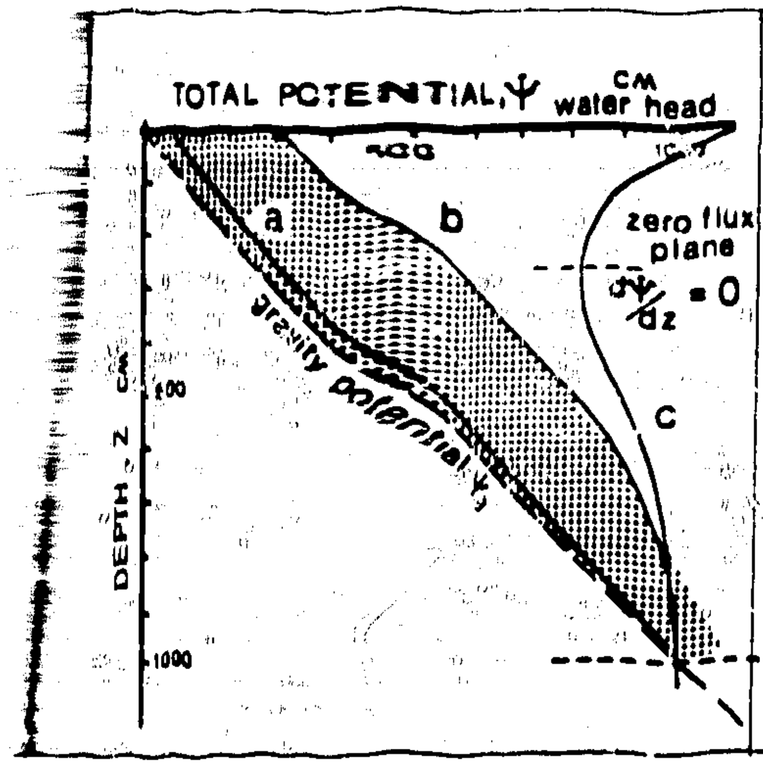


FIGURE 3.2

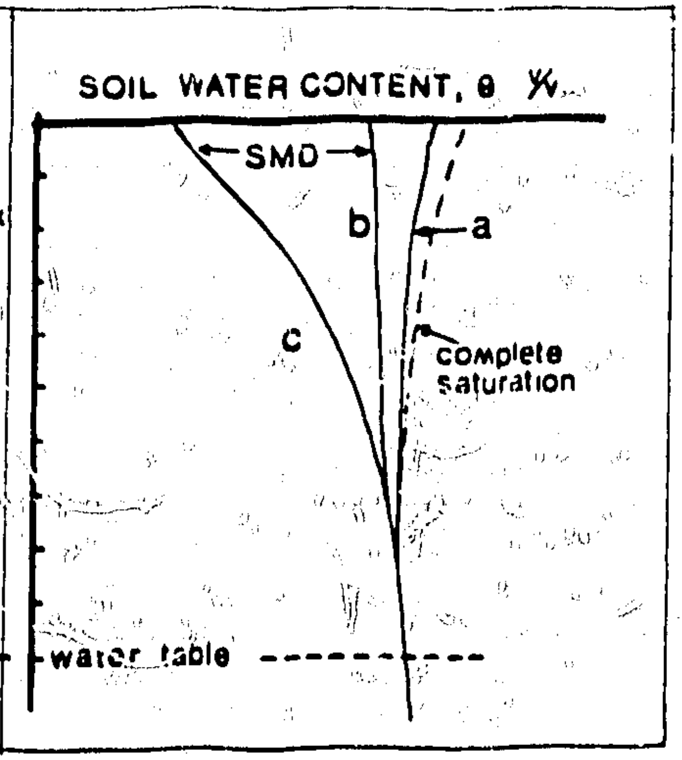


FIGURE 3.3

tivity permits rapid drainage to continue until the potential gradient tends to zero and the potential profile is in equilibrium with the water table (Fig. 3.4).

If the water table is shallow and constant in depth, field capacity is represented by the water content profile (a) on the right-hand side of Fig. 3.4; this corresponds to the potential profile (a) shown on the left of the figure. However, a fall in the water table to B will cause the equilibrium profile to readjust and a different moisture content profile (b) will result. Thus, every water level has its own associated field capacity value and this presents further difficulties.

The real difficulty arises however in what may be termed the "hybrid" situation, which applies to most soils, which have intermediate conductivity and deeper water tables. Here, relatively large and prolonged contributions to drainage can be released from the lower part of the profile while the upper part is providing upward fluxes to supply crop water abstraction. Excess cumulative

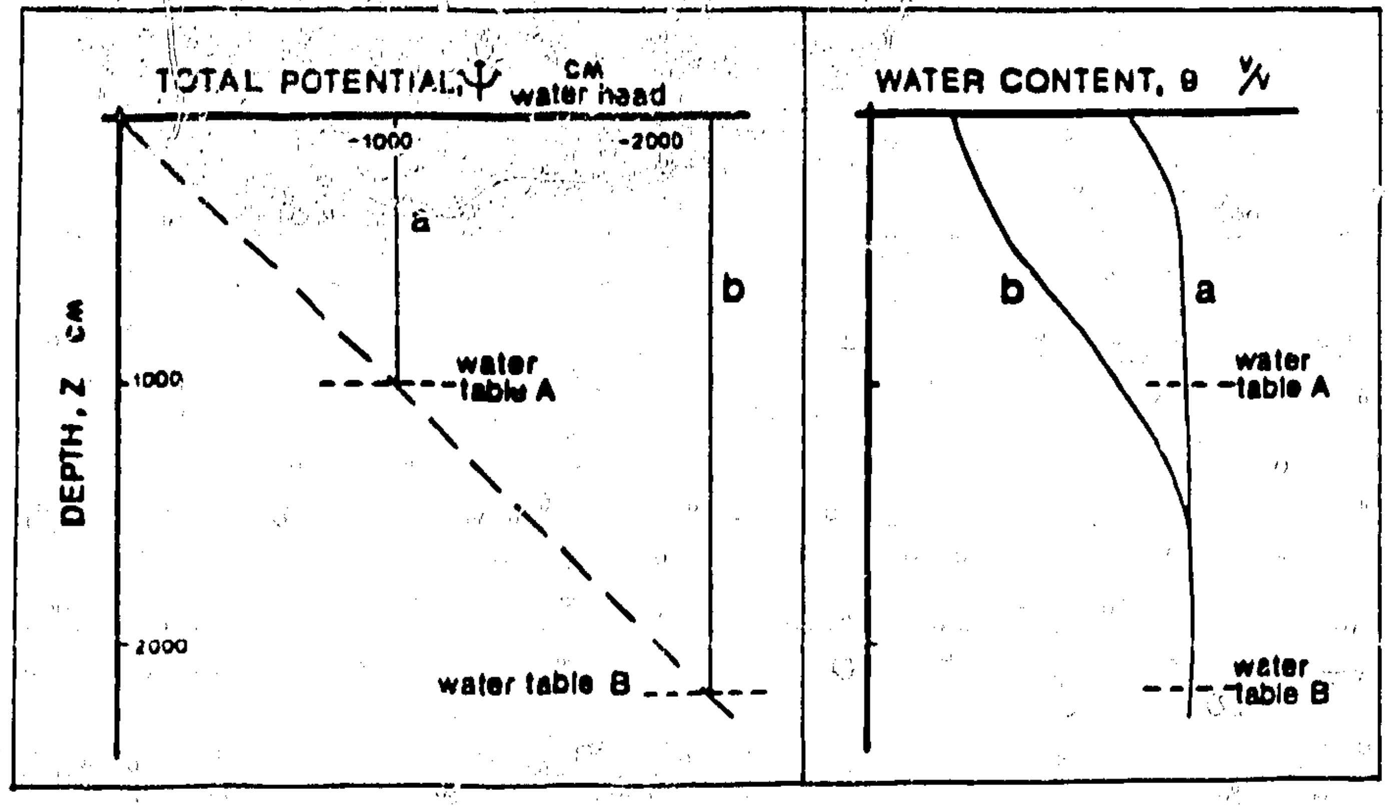


FIGURE 3.4

evaporation over rainfall in the summer creates a divergent "zero flux plane" in the potential profile. The zero flux plane (ZFP) corresponds in a potential profile to a point where the potential gradient, $d\psi/dz$, is zero and defines the position of the divide between zones of upward flux and downward flux (see profile (c), Fig. 3.2). As the summer progresses the ZFP moves downward, reaching a fairly constant depth by mid-summer (Fig. 3.5).

Autumn rainfall re-wets the profile from the surface (creating a convergent ZFP) and this moves quickly down the profile until it meets with, and cancels out, the original divergent ZFP; through drainage is then re-established. Heavy summer rain can have the same effect, permitting a short period of through drainage.

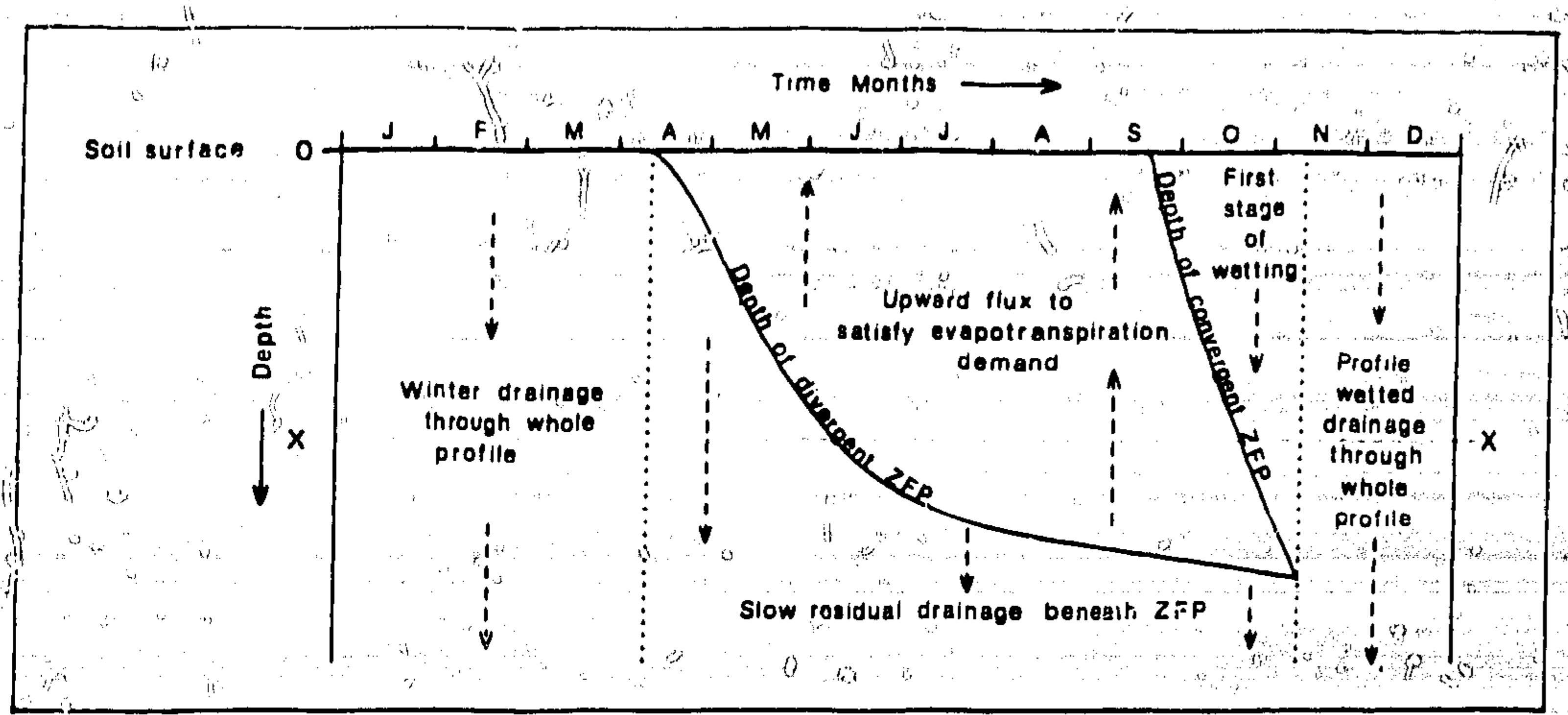


FIGURE 3.5

It should perhaps be mentioned that the presence of a ZFP does not entirely preclude the possibility of brief periods of recharge. This could arise in some soils if the rainfall was sufficiently intense to create "macropore" flow, through fissures or root channels, bypassing the matrix. It could also arise if surface runoff caused localised ponding which could concentrate the input sufficiently to replenish entirely any deficit at those places.

Whatever depth of profile is considered therefore, it is impossible to avoid either upward or downward fluxes (or both) crossing the base during the so-called "deficit" period and MORECS does not recognise this. *In fact, the meteorological model is, in reality, predicting the deficit in the layer of constantly changing depth above the zero flux plane.*

Furthermore, in the hybrid situation there is no reproducible field capacity profile; in the winter the water content profile is constantly changing, representing the balance between long term continual drainage on one hand and rainfall and evaporation on the other. Thus:

(1) The meteorologically predicted SMD relates to a changing depth of profile above the ZFP and is therefore not comparable with moisture contents integrated over a constant depth of profile, as normally measured in the field.

(2) There is no reproducible field capacity state.

For practical irrigation purposes the meteorological model in its present form, ie predicting the deficit above the zero flux plane, may be most appropriate because by replenishing this (partial) deficit, little or no water is likely to be wasted by drainage. It should not be expected however, to agree with soil moisture deficit monitored for a constant depth of soil profile.

The hydrologist, on the other hand, has to consider the full depth of the profile and here the lower component of deficit should probably also be taken into consideration by including a drainage term in the model.

Conclusions

Several problems arise from the foregoing discussions which are particularly relevant when comparing MORECS predicted SMDs with measured SMDs to assess the accuracy of MORECS.

(1) There is likely to be a discrepancy between the measured and predicted dates from the onset of deficit conditions in the spring; this can arise from two sources. The first is the uncertainty in defining a measured field capacity datum. The second arises from any error within MORECS in the balance between Ep and rainfall, which determines whether or not there is a deficit; if Ep is, (for example) overestimated, deficit conditions will apparently start earlier. Thus, the two time series deficit curves can be displaced in terms of deficit for the entire summer season. The assessment of any errors attributable to MORECS arising from this situation is thus difficult to resolve.

(2) It is not clear whether 'deficit' should be considered to relate to a constant profile depth and hence include an unquantifiable drainage component (which may be significant in some soils), or whether it should relate to a changing but unknown depth of profile above the zero flux plane. Measured deficits represent the first situation and predicted deficits the second. Is a direct comparison therefore valid?

(3) If deficits are conceived of as relating to a constant profile depth, how should that profile depth be defined and how can provision be made for different soil/crop/water table situations?

It is possible to argue therefore that soil moisture deficit is a meaningless concept for many soils, whether measured or predicted, and that it might be wiser to restrict the MORECS model to the prediction of actual evaporation.

The arguments that have been presented here are largely speculative. The full comparison between MORECS data and the measured values in the databank should reveal to what extent and in what circumstances the problems outlined are of practical importance and highlight where any improvements need to be made in the model.

4 PRELIMINARY COMPARISONS BETWEEN MORECS AND MEASURED SOIL MOISTURE DEFICITS

C M K Gardner, Institute of Hydrology

Comparisons have been made between soil moisture deficits (SMD) measured at grassland sites in southern England and MORECS SMD values. These comparisons can only be regarded as preliminary for it has not been possible to use estimates prepared by the new version of the MORECS system which is to be introduced in May 1981. The Meteorological Office has not as yet been able to re-run MORECS for past years. As an interim measure, M Field of the Meteorological Office has prepared a near equivalent to the version of MORECS which has been operative from April 1980. This "quasi-MORECS" uses data from individual meteorological stations to produce point estimates of SMD rather than areal estimates generated by the full system. Although the meteorological input is thus slightly different, the method of calculating potential evaporation and the soil moisture extraction model used are identical to those used in MORECS prior to May 1981.

SMD estimates were prepared using this model and meteorological data from ten stations chosen for their proximity to soil moisture measurement sites which are included in the recently compiled soil moisture databank (Gardner 1981). The model was run using all three MAX values for grass crops (50 mm, 64 mm and 80 mm).

The soil moisture measurement sites

Soil moisture changes were monitored by neutron probe at the 38 field sites, by various organisations, for periods of two years or more between 1972 and 1979. Most of the sites are within 40 km of the meteorological stations (Fig. 4.1). The sites are all grassed, level or gently sloping, and include sandy, loam, clay and chalkland soil types. At most sites replicate measurements of soil moisture had been made in two or more access tubes but for the purpose of the comparisons means were calculated.

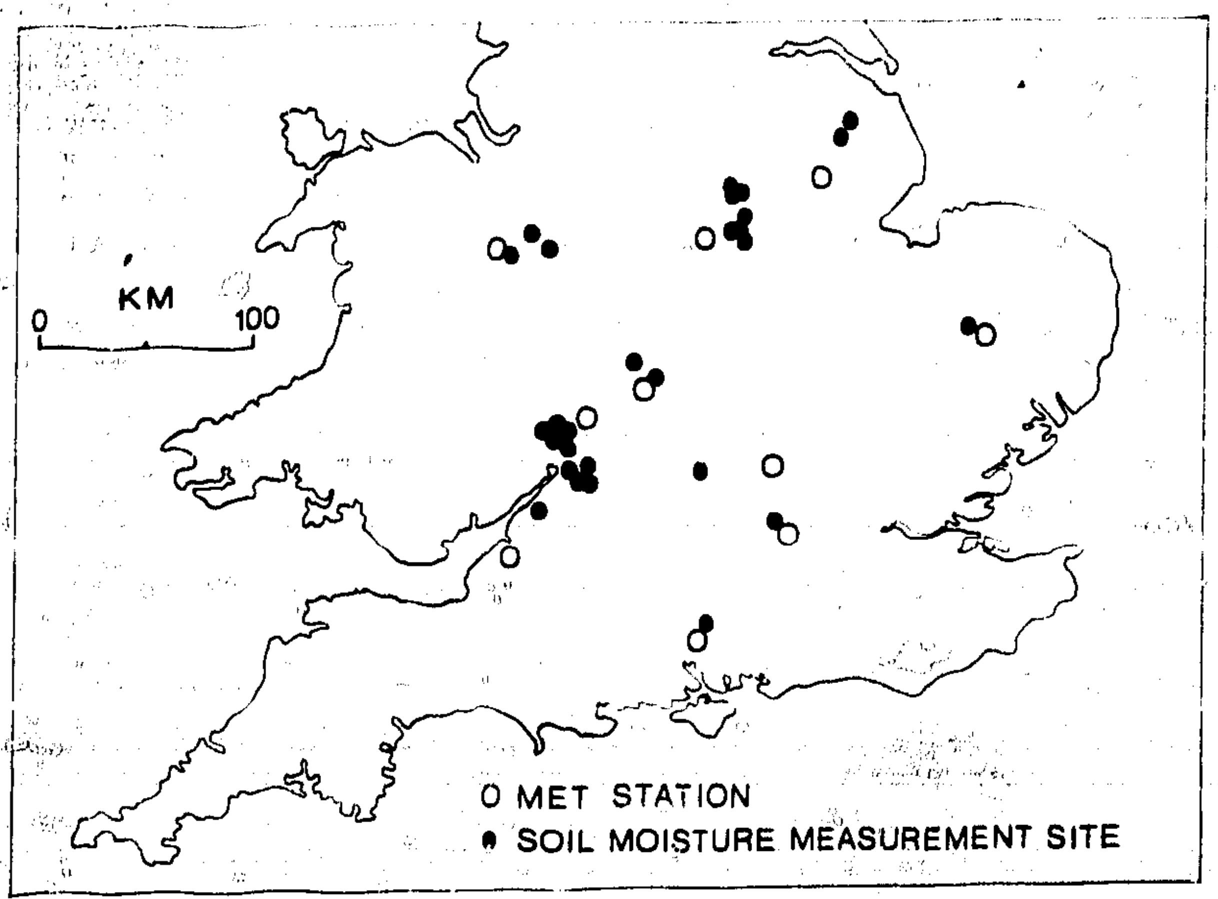


FIGURE 4.1

The distributions of the soil moisture measurement sites and the meteorological stations

Definition of soil profile depth and field capacity

Soil moisture deficits were calculated only for the top metre of the soil profiles as at many of the sites measurements had not been made to greater depths. Field capacity was defined as the lowest decile of the profile moisture content measurements made during the months of January, February and March, of each year of measurement (except 1976) at each site. At those sites for which too few winter measurements were available to calculate a lowest decile value, the lowest moisture content measured during the same periods was used.

This definition of field capacity is rather arbitrary but was adopted in preference to attempting to fit field capacity values to the data from each site. It assumes that for much of the first three months of each year soils are wetter than field capacity. The beginning of 1976 was excluded for many soils did not wet up fully over the 1975-76 winter.

Results

Initially, comparisons were made with MORECS estimates which had been prepared using the MAX value which seemed appropriate to the soil type at each site. When the measurements and the estimates of soil moisture deficit were compared graphically (Figs. 4.2, 4.3, 4.4) it was found that there was reasonable agreement between the timing of the peaks and troughs of the pairs of curves and in some instances between the timing of the onset and termination of the main deficit period each year.

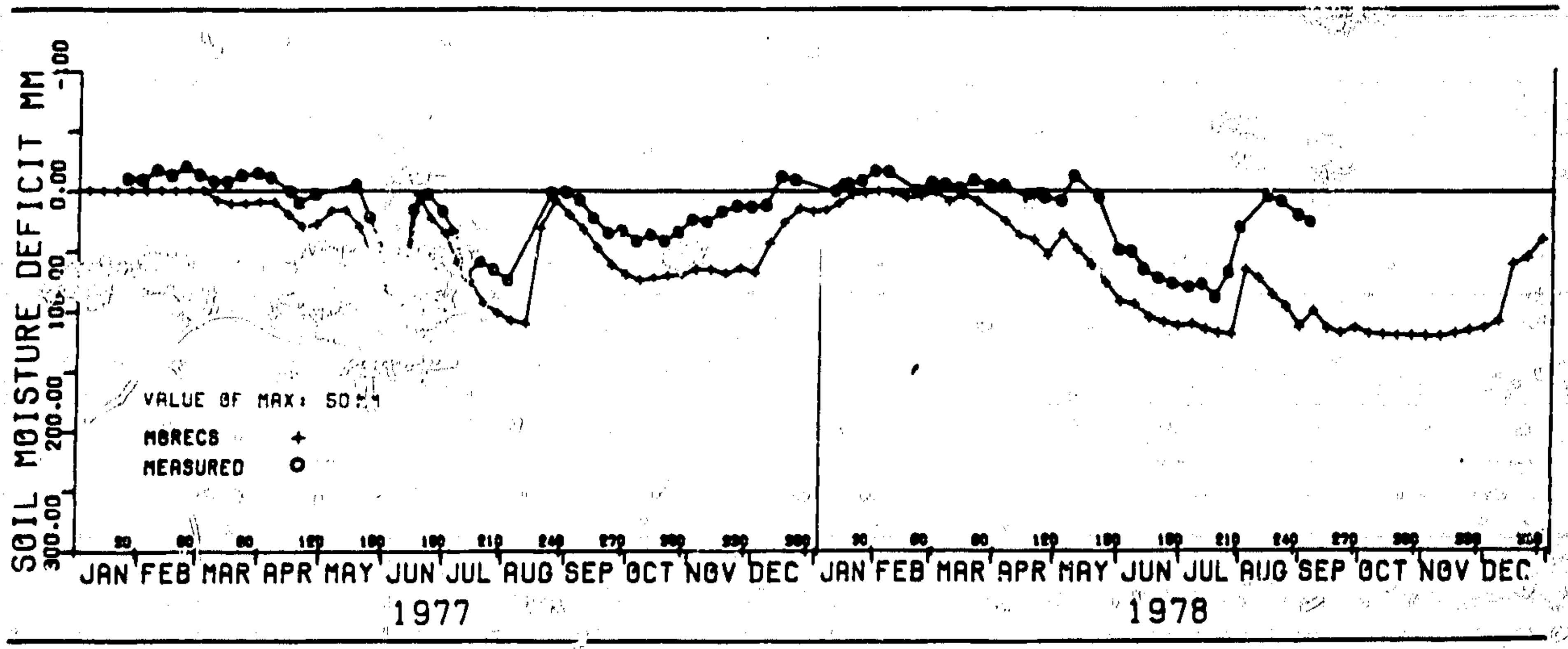


FIGURE 4.2 **Comparison between MORECS and measured SMDs at Wellesbourne (Warwickshire) in a sandy alluvial soil**

MAX = 50 mm RMS = 37 mm

However it was apparent in almost all the examples that MORECS fairly consistently overestimated the deficit measured in the top metre and the SMD estimates produced to represent the Gloucestershire sites suggested that in most years the soils did not return to field capacity which clearly contradicted the field evidence. The data were compared quantitatively by calculating the root mean square

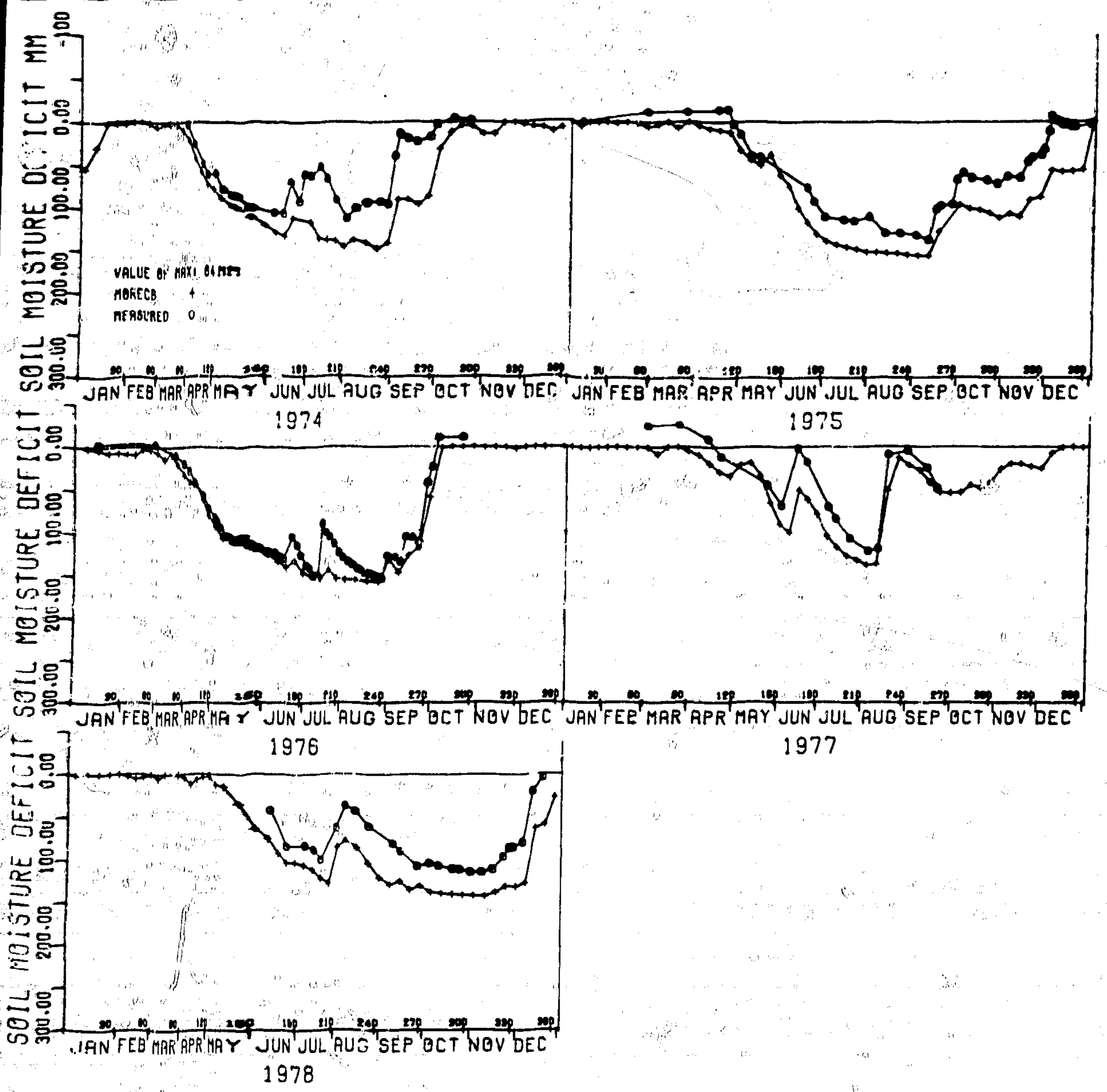


FIGURE 4.3 Comparison between MORECS and SMDs measured on chalkland at Hurley (Berkshire)

MAX = 64 mm RMS = 34 mm

of the differences (RMS) for those periods when either or both sets of data indicated that there was a deficit. MORECS does not estimate negative deficits and so comparisons during such periods, occurring during winter, were not attempted.

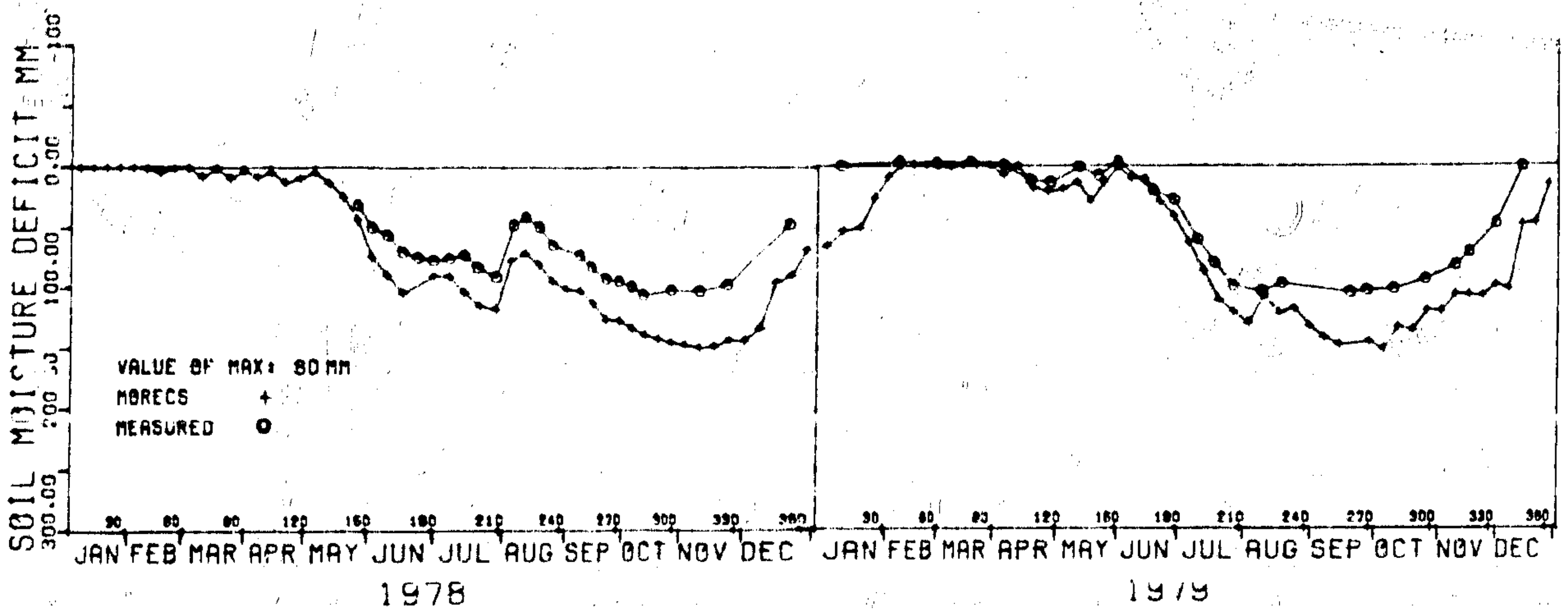


FIGURE 4.4 Comparison between MORECS and SMDs measured at Wytham (Oxfordshire) in a clay soil

MAX = 80 mm RMS = 30.2

Taking the whole sample it was found that the RMS values ranged from 18 mm to almost 100 mm. The mean of the sample was 55 mm. The large discrepencies were principally due to MORECS over-estimating the deficits. When instead of using the MAX values appropriate to the site soil type, the smallest, 50 mm MAX value was used for all sites, the mean RMS was reduced to 38.5 mm (Fig. 4.5).

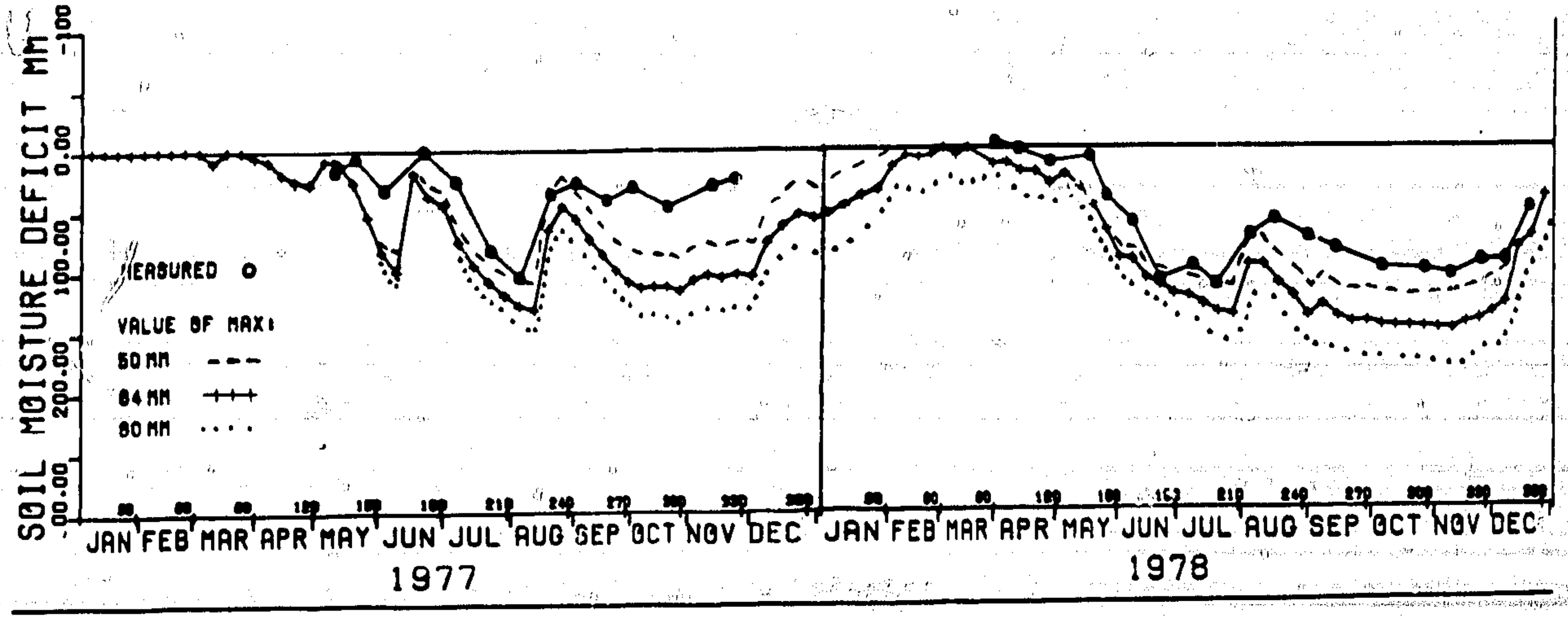


FIGURE 4.5 Measured SMDs from a loam soil near Hartpury (Gloucestershire) and MORECS estimates prepared using the three MAX values for grassland: 50, 64 and 80 mm

When the RMS values were grouped according to soil type, it was apparent that the best fits were for the five chalkland soils included in the sample, with MAX set at 50 mm. Two examples are shown in Figures 4.3 and 4.8. The RMS values ranged from 19 to 32 mm. MORECS over-estimated the SMD except during the latter part of drier summers, eg 1975 and 1976. The RMS values within the other soil groups were much more variable. It should be noted, however, that this result could have been very different if a profile depth greater than 1 m had been adopted.

Reasons for over-estimation

MORECS may appear to over-estimate SMD relative to the measured values because the system is at fault, or because the basis used to define the measured deficits is inappropriate. Errors could also have been introduced in this comparison if the chosen meteorological stations did not represent the soil moisture measurement sites reasonably well. However, as the full MORECS system only uses one set of meteorological data to produce the potential evaporation estimates which represent each 40 by 40 km grid square, the errors are likely to be similar to those which would be obtained were a comparison to be made using the grid square SMD values prepared by full MORECS.

There are three possible explanations as to why MORECS itself might over-estimate the deficit; these are not mutually exclusive.

1 The calculated potential evaporation value (Ep) might be too high.

2 The MAX values could be too large.

3 The relationship of the Ea:Ep ratio with SMD which comes into effect when the SMD exceeds MAX may be inappropriate.

The Meteorological Office had been aware for some time that MORECS' potential evaporation values have been high relative to those obtained by other methods.

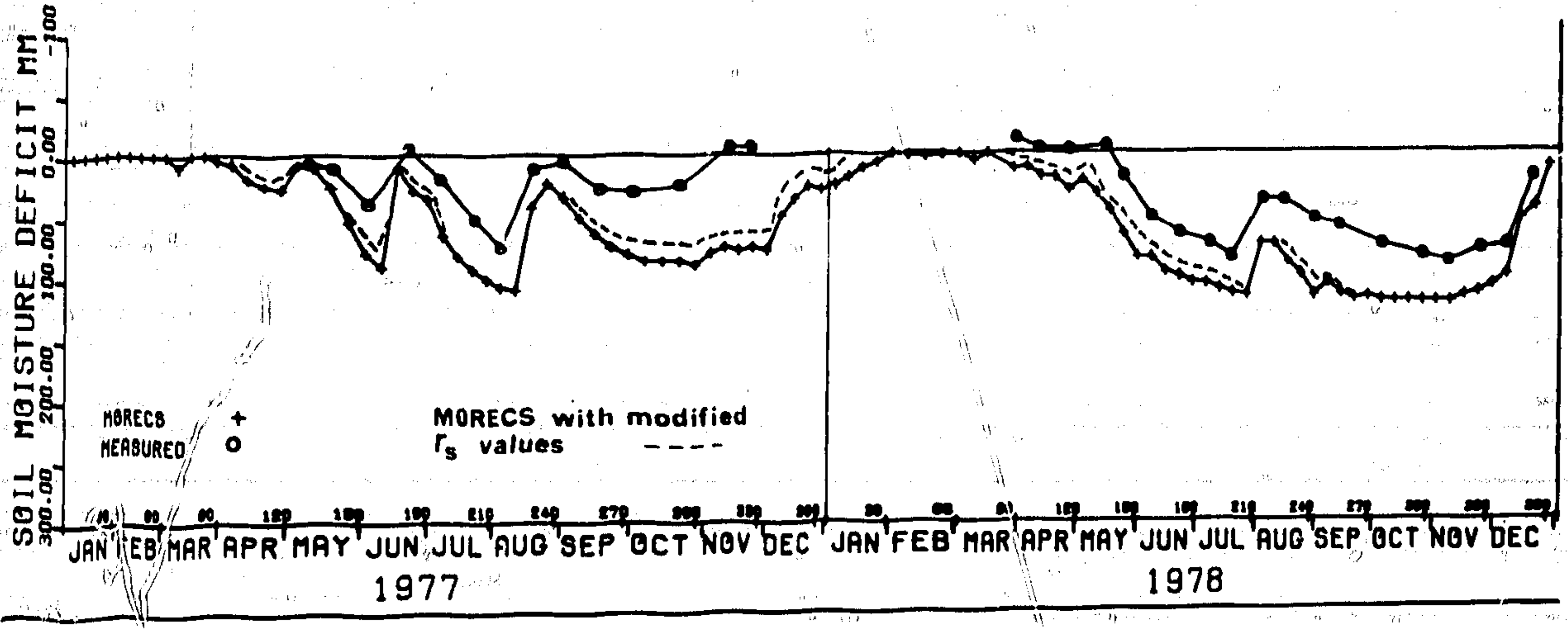


FIGURE 4.6 SMDs measured at a Gloucestershire site compared with MORECS SMDs prepared using both standard and modified r_s values (MAX = 50 mm)

This was thought to be due to the use of rather low surface resistance values with the Penman-Monteith equation. Surface resistance values for grass of 30 sm^{-1} were used for the period April to September and increased to 50 sm^{-1} during the winter months. Looking closely at the comparisons there was evidence that the MORECS Ep values were generally too large; often the deficit period commenced too early and the deficit built up more rapidly than that measured early in the season. The quasi-MORECS was re-run for the Gloucestershire meteorological site with the surface resistance set at 50 s m^{-1} in summer and 80 s m^{-1} in winter. This reduced the size of the SMD estimates as expected and improved the match with the SMDs measured at nearby sites to a certain extent, as shown in Figure 4.6.

The effect of reducing the MAX value is twofold (Fig. 4.7):

1 The developing SMD reaches the MAX threshold earlier in the season and so the consequent reduction in evaporation rate is introduced earlier.

2 The maximum allowable deficit (2.5 MAX) is smaller and is reached sooner.

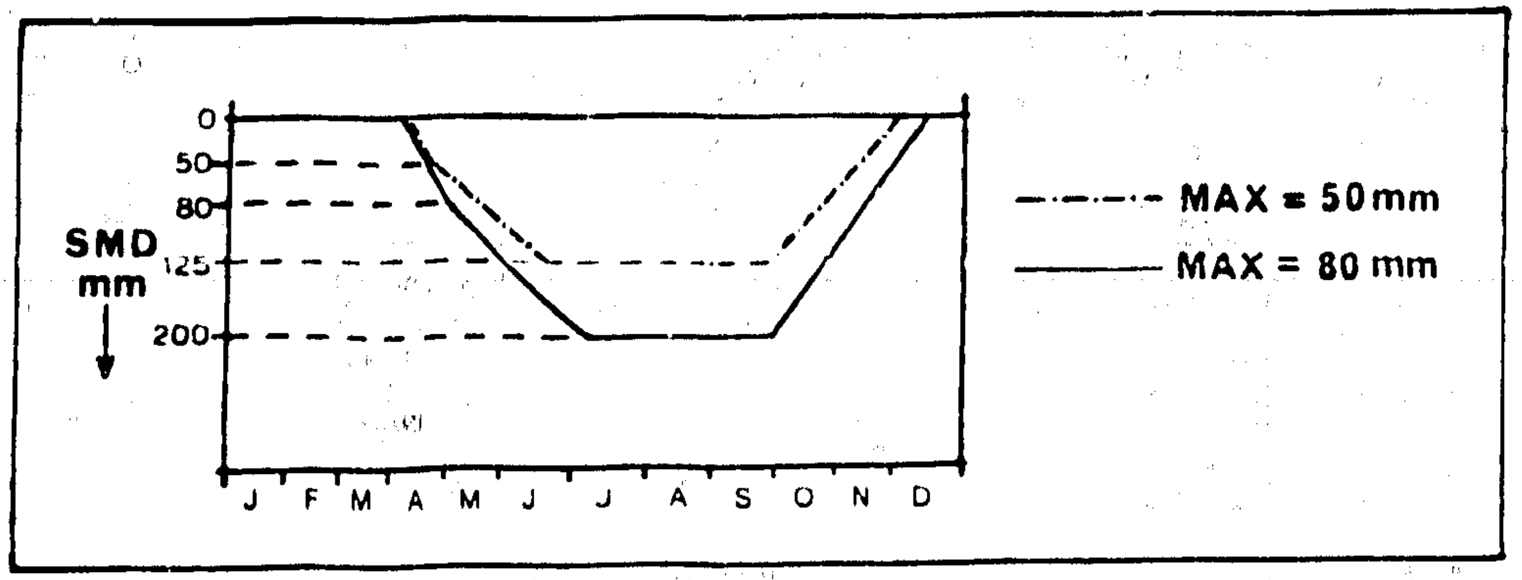


FIGURE 4.7 The effect of reducing MAX on MORECS SMD estimates. In the diagram MAX is changed from 80 to 50 mm, the MAX threshold is therefore reached earlier in the season, and the maximum deficit is smaller and achieved sooner

The second effect was more important in improving the fit between MORECS and the measured SMDs in this sample of comparisons. This was because according to MORECS, regardless of the MAX value used, the maximum allowable deficit was usually reached, even in the relatively wet summers of 1977, 1978 and 1979, although the largest measured SMDs in these years were generally between 100 and 120 mm. Thus using the same Ep estimates an improved match of MORECS to the measured SMDs could be obtained by using smaller MAX values. However, the existing maximum allowable deficits of 125 mm, 160 mm and 200 mm appeared to be more appropriate, for during the drought of 1976 the greatest deficits achieved in the top metre ranged from 115 mm to 200 mm at the sample field sites.

Retaining the 50 mm, 64 mm and 80 mm MAX values for grass, a better fit could also be obtained if the relationship between the Ea:Ep ratio and SMD, when SMD exceeds MAX, was changed such that actual evaporation rates were slower than at present. But given the uncertainty regarding the Ep values, it is not possible to indicate exactly from these data what relationship would be more suitable.

The errors apparent in this comparison may not be entirely due to MORECS, but could result partly from the definitions of profile depth and field capacity used.

There is no indication in the MORECS definition of SMD as to what soil profile depth this refers. Increasing the profile depth considered usually increases the measured SMD significantly and thus improves the agreement; for example, SMDs measured in the [illegible] and 2 m profiles of a chalk soil are shown in Figure 4.8. There are large moisture content changes in the chalk between [illegible] and 2 m depth during the summer because plant abstraction of moisture in the rooting zone above results in an upward movement of water to the roots. For this site, the match with MORECS in 1977, 1978 and 1979 improved when a 2 m profile was considered. However in the dry summer of 1976 MORECS seriously underestimated the deficit in the 2 m profile.

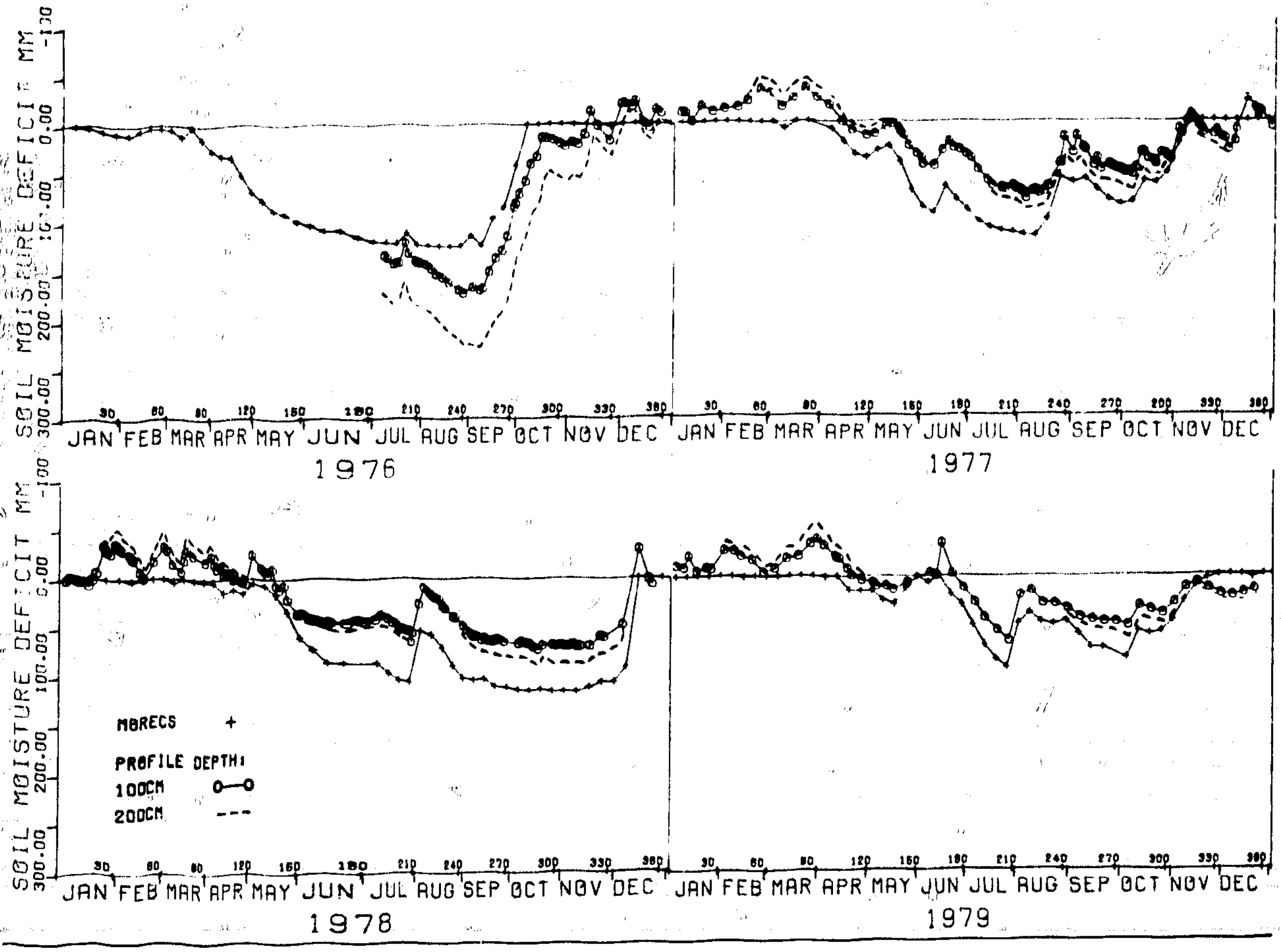


FIGURE 4.8 **Measured SMDs for the 1 m and 2 m deep soil profile at Bridget's Farm (Hampshire) where there is a shallow chalk soil, compared with MORECS**

MAX = 50 mm **RMS(1 m) = 32 mm** **RMS(2 m) = 38 mm**

Changing the field capacity values for the field sites makes the measured SMDs larger or smaller depending on whether field capacity is increased or decreased, respectively. For those sites for which MORECS persistantly over-estimated the deficits, increasing the field capacity values thus also resulted in closer agreement.

Conclusions

The overall impression gained from these preliminary comparisons was that for many of the sample sites MORECS estimated the relative changes in SMD in the top 1 m of soil tolerably well, but not the absolute values. For certain sites the fit was quite acceptable in some years. However the current version of MORECS evidently tends to over-estimate soil moisture deficits for the top metre at least. It is apparent that the agreement between the two datasets could have been improved in most years by altering the MAX values using in MORECS, for example, or the measured profile depth considered. Doing so, however, would not necessarily improve the fit for 1976 when exceptionally large deficits developed. Any future changes to MORECS should not only reduce the SMD estimates for average years but also allow for extremely dry years.

The incorporation of more appropriate surface resistance values into the system as from May 1981 should improve the SMD estimates but until this comparison can be repeated with the new full version of MORECS and using data from more sites representing different crop and soil types, it is not possible to anticipate how well the system will behave in future. The importance of recognising that measured SMDs are influenced by the field capacity datum and the profile depth used to define them has been emphasised in this and the previous paper and should be considered in all comparisons of measured and predicted SMDs.

Acknowledgements

The funds for this work were provided by the Department of the Environment and the Ministry of Agriculture Fisheries and Food. Much of the soil moisture data were provided by organisations and individuals outside the Institute of Hydrology and their co-operation is greatfully acknowledged.

5 THE PREDICTION OF SOIL MOISTURE DEFICIT : AN OPERATIONAL APPROACH

I R Calder, R J Harding and P T W Rosier, Institute of Hydrology.

Introduction

This paper is concerned with exploring ways in which the performance of soil moisture deficit models may be improved by the inclusion of more detailed equations for estimating both potential evaporation and more complex root constant functions which relate actual evaporation to potential via the moisture status of the soil.

The Data

Some three thousand neutron probe observations of total soil moisture content of the profile were used in this study. They were obtained from experiments carried out by the Institute of Hydrology (not specifically for this paper). A description of the six sites is given in Table 1.

TABLE 1 DETAILS OF SOIL MOISTURE MEASUREMENT SITES

Site/ G R	Altitude (m)	Annual rainfall (mm)	Vegetation	Dominant species	Soil Type
Plynlimon SN815855	500	2200	Upland sheep pasture	*Molinia caerulea* *Festuca ovina* *Nardus stricta*	Hireathog series, peats and shallow podzol soils overlying impermeable slaty mudstones.
Bridgets Farm SU518340	85	790	Simulated pasture	*Lolium perenne* *Dactylis glomerata* *Agropyron repens*	Andover series, 30 cm silty clay loam overlying chalky drift and main chalk.
Fleam Dyke TL539549	30	540	Short mown grass	*Dactylis glomerata* *Holcus lanatus* *Festuca rubra*	30 cm calcareous brown earth overlying middle chalk
Cam TB536423	107	580	Mixed pasture/ meadow	*Lolium perenne* *Dactylis glomerata* *Phleum pratense*	100 cm brown calcareous soil overlying boulder clay.
Grendon SP678208	76	[illegible]70	Pasture/ meadow	*Lolium perenne*	Denchworth, Evesham, Tile House, Rowsham, Knowl Hill series, 100 cm clay loam merging into Oxford clay
Thetford (forest clearing) TL799836	50	550	Ungrazed heath/ grassland	*Agropyron repens*	Worlington series, sandy soil of varying depth (30-120 cm) overlying chalky drift and main chalk

Method

The study started with the simplest conceivable soil moisture deficit (SMD) prediction model and then assessed what improvements in accuracy of prediction could be obtained by incorporating progressively more detailed equations for estimating potential evaporation and root constant regulating functions as illustrated schematically in Figure 5.1.

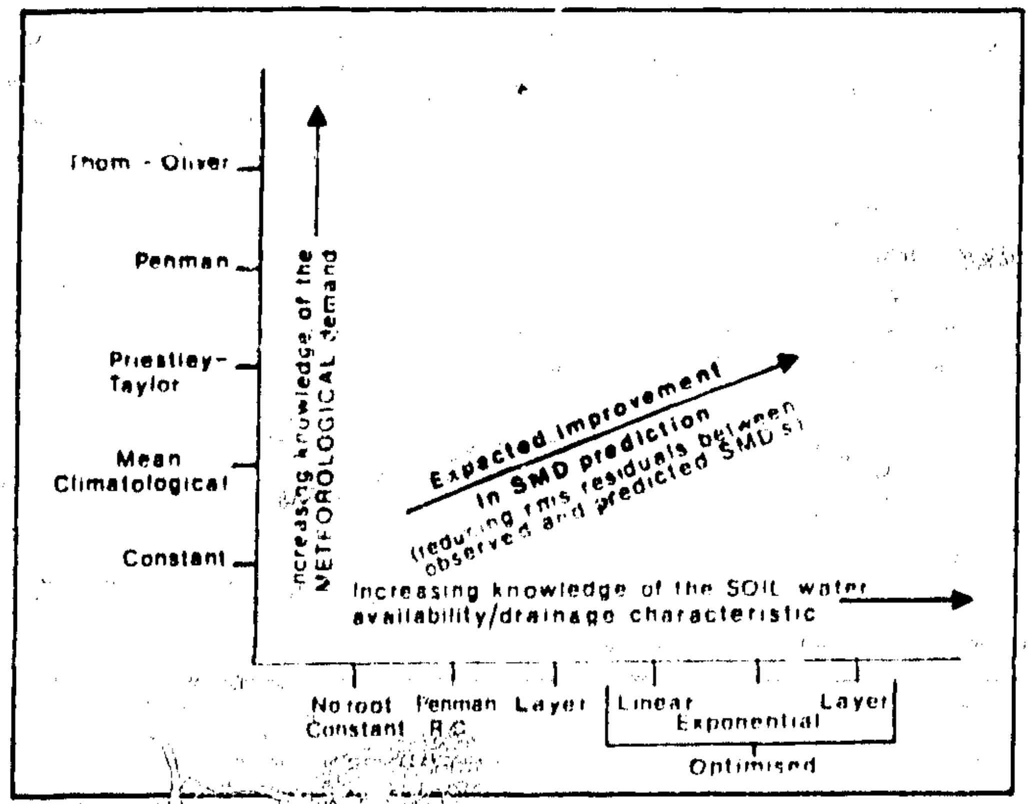


FIGURE 5.1

The expected improvement in model fit as a function of increasing knowledge of the root constant functions and evaporation estimates

All model formulations are based on the following four assumptions:

1 That there is no soil water drainage when the moisture content of the profile is below "field capacity";

2 the moisture content of the soil, if exceeding field capacity, will, in the absence of precipitation, return to field capacity after one day;

3 the change in moisture content of the soil is equal to the precipitation minus the evaporation that occurs on a particular day;

4 the actual evaporation is equal to potential evaporation multiplied by a root constant regulating function.

The mathematical formulation of the model is then given by:

$$\hat{SMD}_{i+1} = \hat{SMD}_i + E_i - P_i \qquad \hat{SMD}_i > 0$$

$$\hat{SMD}_{i+1} = E_i - P_i \qquad \hat{SMD}_i < 0$$

Where at the experimental site under consideration:

$\hat{SMD}_i$ = SMD predicted on day i

P_i = Precipitation on day i.

E_i = Evaporation on day i.

Field capacity values were obtained by an optimisation procedure in which trial field capacity values were adjusted until the best fits were obtained between winter values of observed and predicted SMDs. The objective function is given by:

$$O.F. = \sum_{i=1}^{nd} \sum_{j=1}^{nt} (SMD_{i,j} - \hat{SMD}_i)^2 \quad \text{for } \hat{SMD}_i < 30 \text{ mm and } SMD_{i,j} \text{ defined by:}$$

$$SMD_{i,j} = FC_j - MC_{i,j}$$

nd = final day number with observations

nt = number of tubes

and

FC_j = field capacity value for tube j,
i.e. the value being optimised

$MC_{i,j}$ = moisture content observed (for tube j on day No. i).

For this procedure an SMD model which assumes an evaporation equal to Penman's Et without a root constant function was used. Because only winter values are considered the field capacity values found were essentially independent of the model used.

Thirty different models were formulated using all combinations of five component potential evaporation equations and six component root constant functions. The potential evaporation formulations with their data requirements are described in Table 2; the root constant regulating functions are shown in Figure 5.2a for the unoptimised functions and in Figure 5.2b for the functions in which one parameter was optimised at each site.

TABLE 2 DETAILS OF POTENTIAL EVAPORATION EQUATIONS USED IN THE ANALYSIS

	Source	Equation (mm day^{-1})	Data requirement
Constant		$E_t = 1.37$	Mean annual total Penman PE for UK
Climatological	Smith (1967)	$E_t = 1.5.(1+\sin(\frac{i.360}{365} - 90)$	Mean monthly Penman for UK
Priestley-Taylor	Priestley-Taylor (1972)	$E_t = \frac{\alpha \cdot \Delta Rn}{\Delta + \gamma}$	Daily temperature and sunshine from local site
Penman	Penman (1948)	$E_t = \frac{\Delta \cdot Rn + \gamma \cdot Ea}{\Delta + \gamma}$	Daily temperature, sunshine, wind and humidity from local site
Thom and Oliver	Thom and Oliver (1977)	$E_t = \frac{\Delta \cdot Rn + \gamma \cdot m \cdot Ea}{\Delta + n \cdot \gamma}$	ditto

where:
Δ is the slope of the saturation vapour pressure curve (mb^{o}k^{-1})
γ is the psychrometric constant (mb^{o}k^{-1})
Rn is the net radiation equivalent in mm
α, n and m are empirical constants
and Ea = 0.26*(1 + 0.54*u)*VPD where u is the windspeed (m sec^{-1}) and VPD is the vapour pressure deficit (mb)

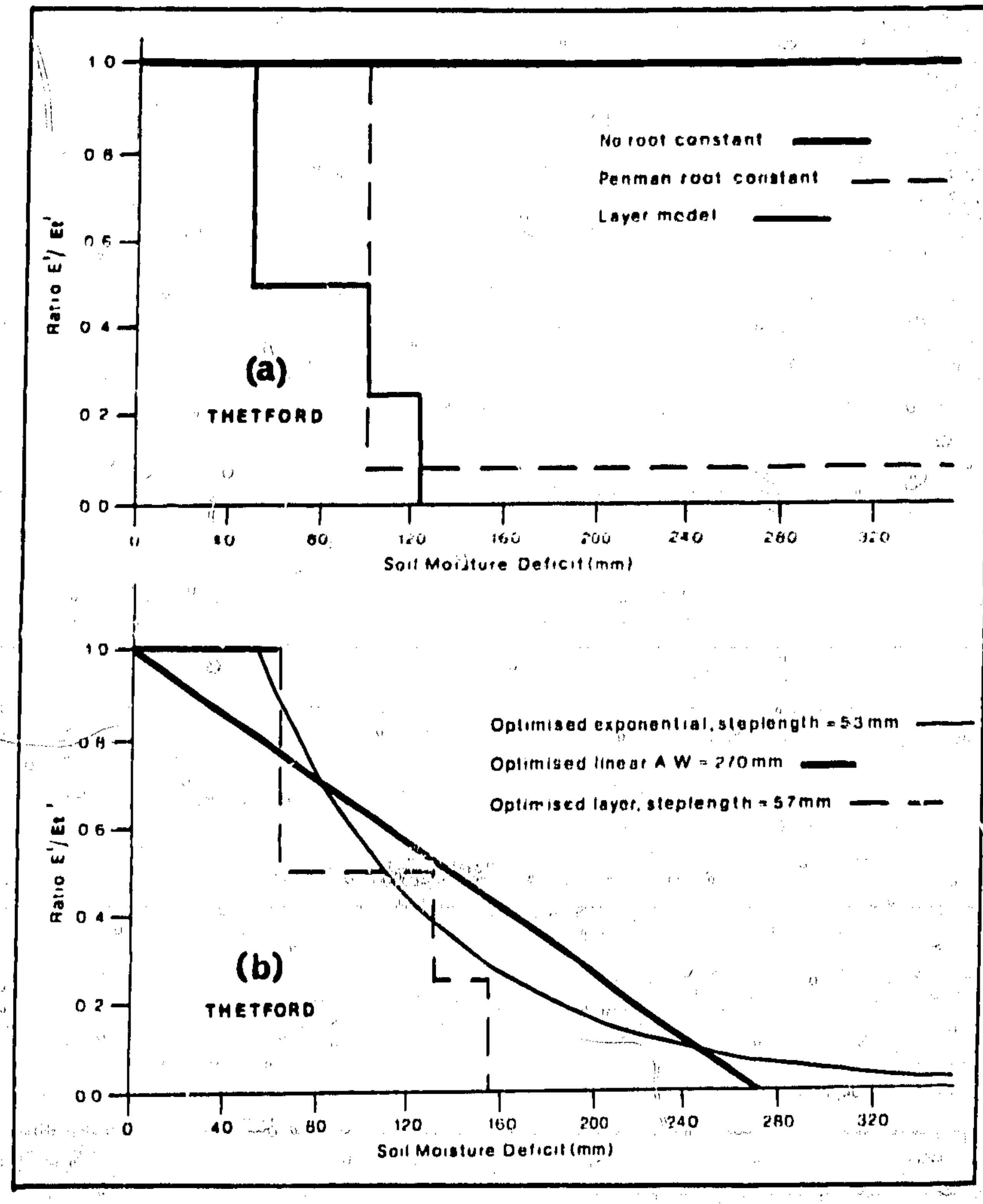


FIGURE 5.2 The forms of the regulating functions used to determine the actual evaporation (E) from the potential evaporation (Et) for a sample site. (a) The unoptimised functions (b) The optimised functions

Model performance was assessed on the basis of the classical goodness of fit criteria involving the summation of the squares of the residuals between observation and prediction. A model error and the standard deviation of the data were then calculated from this sum of squares of residuals (for full details of these quantities, see Calder *et al.*, 1981).

Results and Conclusions

The relative performances of the model configurations over all the experimental sites in terms of the mean of all sites model error is shown in Figure 5.3. A number of general features can be identified:

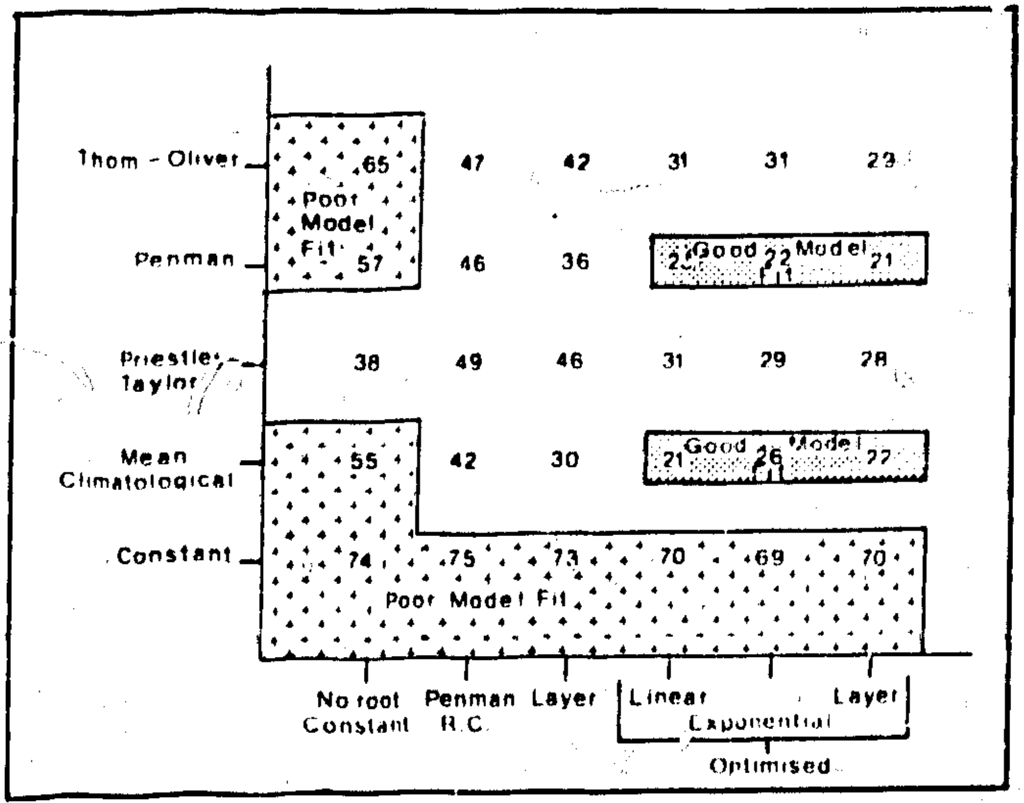


FIGURE 5.3

The mean of all sites model error (mm) for all combinations of root constant functions and evaporation estimates

1 The best model fits are obtained with parameter optimisation. The differences between the model errors for the various optimised model configurations are small.

2 Without parameter optimisation the most successful SMD models are those incorporating the layer regulating function.

3 The potential evaporation equations incorporating either the climatological mean or the Penman formulations are the most successful.

4 The Thom-Oliver and Priestley-Taylor formulations produce relatively poor fits and, as expected, the constant formulation produced the worst model fits.

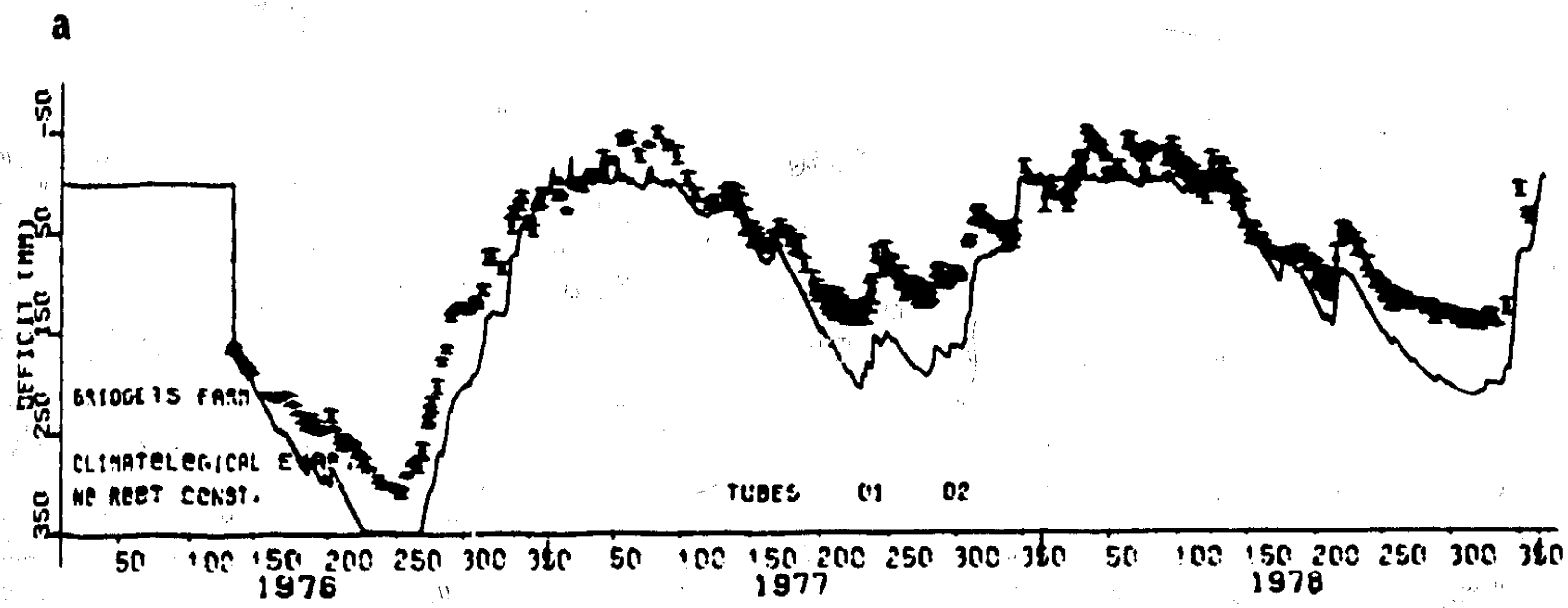
Figures 5.4 and 5.5 show the observations and model predictions, for two contrasting sites, using no root constant (5.4) and an unoptimised layer formulation (5.5). (The results of the analysis for all the individual sites are detailed fully in Calder *et al.* 1981). It is evident that the regulating function which produces the best fit with the observations is very site dependent; on the chalk soils at Bridget's Farm and Fleam Dyke the optimised parameters are relatively large and the use of no root constant produces the best model fit. A similar result is found for the upland, peaty soils at Plynlimon where deficits appear to develop at a rate dictated by the potential evaporation up to the highest deficits observed (100 mm, in the drought of 1976). In contrast, without the use of a root constant, the SMD estimates for the clay soils at Grendon and the Cam and the sandy soil at Thetford are seriously in error.

The success of the climatological mean potential evaporation estimate at all sites and for all years (including the drought year of 1976) clearly demonstrates the remarkably conservative nature of potential evaporation within the UK, both spatially and temporally. It seems probable that on a day-to-day basis grass transpiration does not respond fully to variations in atmospheric demand (ie potential evaporation). This implies that in addition to the SMD negative feedback mechanism which limits transpiration in times of high SMD there is another, independent, negative feedback mechanism which limits transpiration in times of high atmospheric demand.

FIGURE 5.4

The mean observed and predicted SMD values prepared without the use of a root constant, for two contrasting sites

(a) Bridget's Farm (b) Grendon



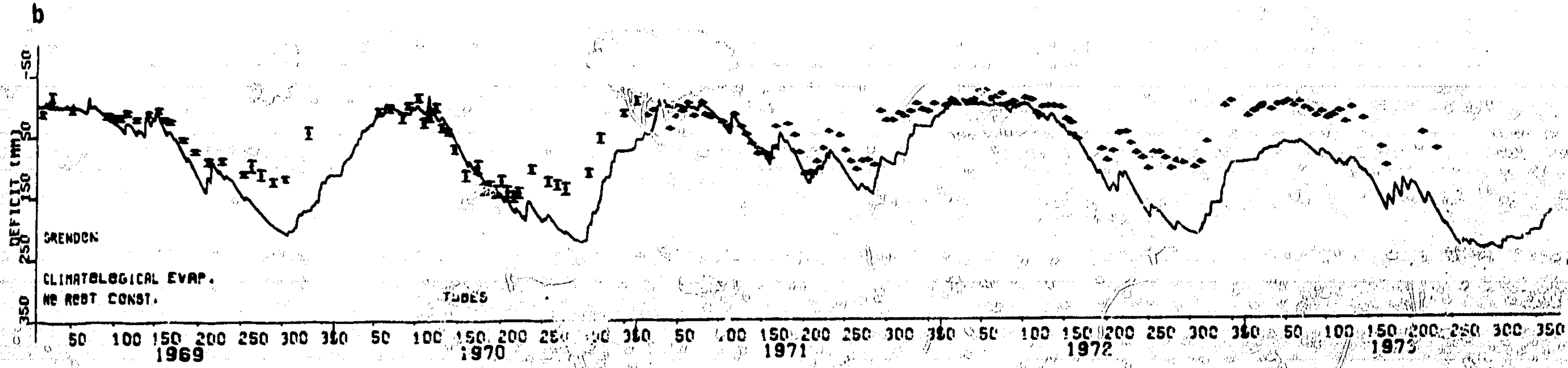
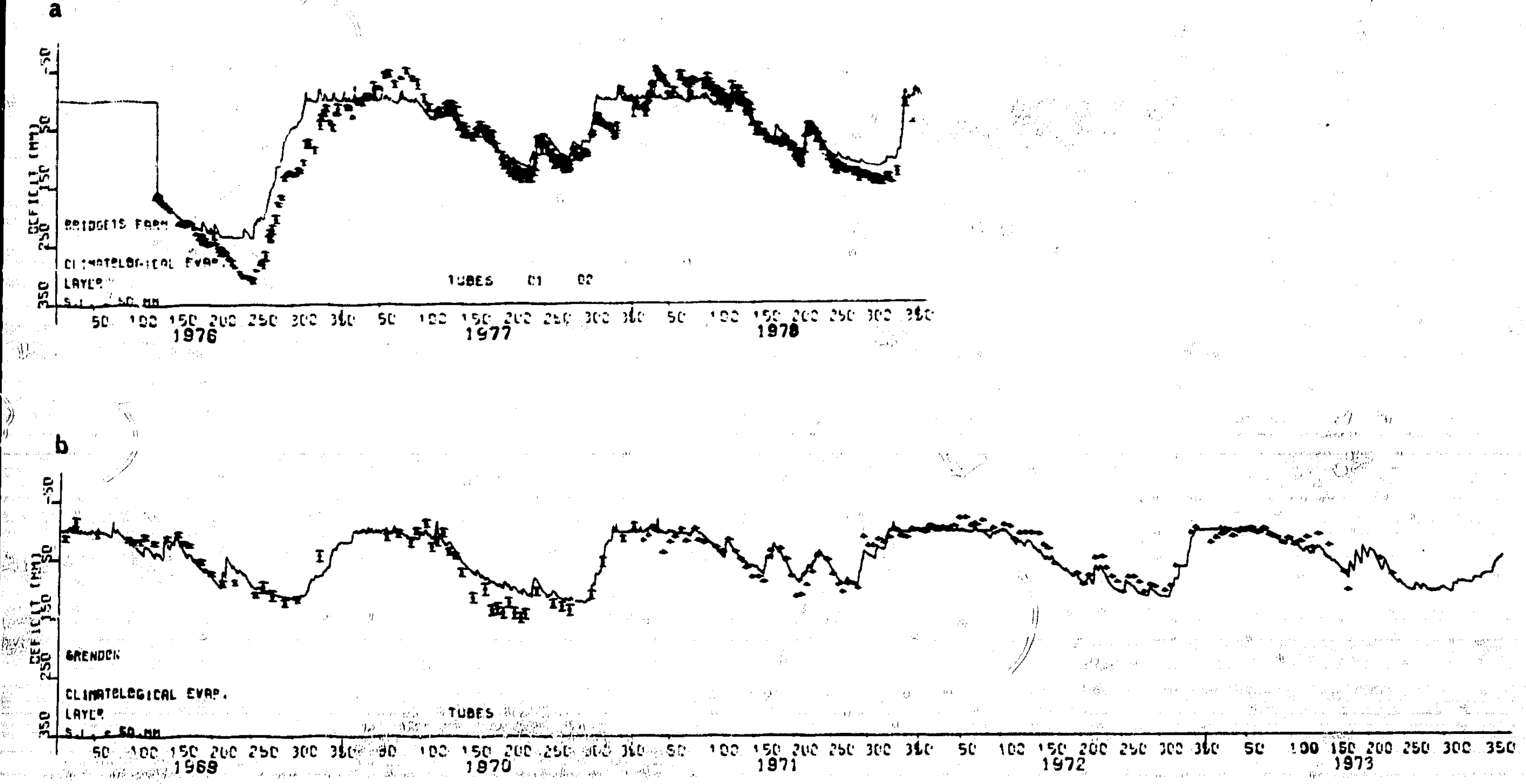


FIGURE 5.5

The mean observed and predicted SMD values prepared using an un-optimised layer formulation

(a) Bridget's Farm (b) Grendon



It can be concluded that more detailed potential evaporation equations do not necessarily result in improved SMD predictions. Indeed, the use of a simple climatological mean estimate of evaporation, which requires no measurement of the meteorological variables (other than rainfall), produces (marginally) the best SMD predictions when used in conjunction with an appropriate root constant regulating function.

It should not be forgotten that the SMD models that have been used in this study are based on gross simplifications of the real system. Inevitably the optimised root constant values that have been obtained will be making allowance for many different possible mechanisms which may modify or change SMDs other than those due to transpiration by the crop, such as the effects of interception, soil moisture drainage, deep abstraction and evaporation from the soil surface. It is the belief of the authors that until these effects are further investigated, and incorporated explicitly in SMD models, little advantage can be gained from further developments of the meteorological aspects of these models.

Calder, I R, Harding, R J and Rosier, P T W. In press. An objective assessment of moisture deficit models. Paper submitted to J. Hydrol.

Penman, H L , 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc., Ser. A, 193, 120-145.

Penman, H L , 1949. The dependence of transpiration on weather and soil conditions J. Soil Sci. 1, 74-89

Priestley, C H B , and Taylor, R J , 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Wea. Rev. 100, 81-92

Smith, L P. 1967. Potential transpiration. MAFF Tech. Bull. No. 16. HMSO.

Thom, A S and Oliver, H R, 1977. On Penman's equation for estimating regional evaporation. Q. J. Roy. Met. Soc.436, 345-357.

6 MORECS: AN AGRICULTURAL PERSPECTIVE

J L Monteith, Department of Physiology and Environmental Studies, University of Nottingham.

Agronomy

Farmers are not interested in the rate of evaporation from crops but in how fast they grow, how much they yield and what profit they produce. When we start to consider the agricultural and horticultural uses of a scheme like MORECS, we have to remember that growers want to know when to irrigate, how much water to apply and what increase of yield can be expected per unit of applied water.

For the main arable crops grown in Britain, all these questions have been explored in detail by Dr Penman and his colleagues at Rothamsted, working first on a light, sand soil at Woburn (Penman 1971) and later on a clay at Rothamsted (French and Legg 1979). Figure 6.1 illustrates the type of response they obtained when the yield of an unirrigated crop (Y) was expressed as a function of the yield (Y_i) from a nearby irrigated crop in the same season. The relative yield Y/Y_i, measured over a number of seasons was plotted as a function of the maximum potential soil water deficit calculated from the records of rainfall and of potential evaporation. For seasons in which the maximum deficit (D_m) was less than a limiting value (D_l), the relative yield was close to unity, but when D_m exceeded D_l the loss of relative yield ($1 - Y/Y_i$) was proportional to $D_l - D_m$.

Physiology: leaves

The physiological interpretation of Figure 6.1 is that there is a range of soil water deficits (0 to D_l) within which growth is restricted by environmental factors, such as light and temperature, rather than by water supply. Outside this range the rate of transpiration and the rate of growth decrease in almost the same proportion. First, both transpiration and growth depend on the fraction of radiation intercepted by a canopy. This fraction is less when leaf expansion is restricted by drought. Secondly, stomatal closure in response to drought limits the diffusion of water vapour and of carbon dioxide. According to a simple resistance model of the system, partial closing of stomata should restrict the loss of water vapour more than the uptake of carbon dioxide which is limited mainly by the rates of biochemical processes. However, the fact that growth and the loss of

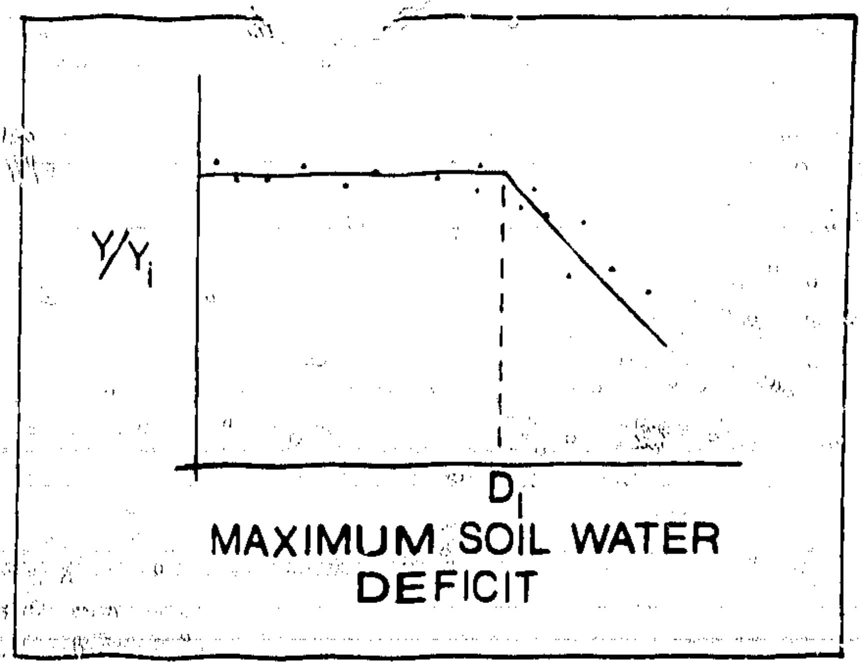


FIGURE 6.1

Determination of limiting deficit D_l by plotting the relative yield from an unirrigated crop against the maximum soil water deficit calculated from the potential evaporation rate in a number of seasons water are so closely correlated is consistent with recent evidence that the concentration of carbon dioxide in sub-stomatal cavities is maintained at an almost constant level in light, at least in some species. Simple analysis predicts that the rate of carbon dioxide uptake should then be proportional to the evaporation rate and inversely proportional to the saturation deficit of the atmosphere (Monteith 1981).

Physiology: roots

The limiting deficit (D_1) is determined by the maximum rooting depth of a crop (usually between 25 and 100 cm for arable and grass crops in Britain), and by the available water per unit depth of soil in the root zone. So the value for a crop growing in Rothamsted clay is about 2½ times the value for the same crop growing in Woburn sand. During the first part of the growing season, the roots of an arable crop move rapidly downwards. In a temperate climate and in agriculturally important soils, root extension into wet soil makes new sources of water available to plants at a rate which is usually less than or equal to the evaporation rate (3 to 4 mm/day). The deficit becomes "limiting" when root extension stops, either as a consequence of physiological control (as in cereals at anthesis), or when downward penetration is inhibited by an impermeable layer of soil. In a semi-arid climate, however, root extension may fail to keep pace with an evaporation rate of 7-10 mm/day and in these circumstances, "limiting deficit" may not be such a useful concept.

Agricultural meteorology

The implication of Figure 6.1 for MORECS, and for any other scheme for calculating evaporation, is that high precision is unnecessary when estimates of irrigation need are supplied to farmers. The objective of an irrigation programme is to maintain the soil water deficit between zero and D_1 by specifying how much water should be applied, and when, but the error in calculating evaporation is only one of a series of uncertainties.

1 The appropriate value of D_1 for a specific crop in a specified soil will rarely be known to better than ±5 mm and will often be uncertain to ±10 mm.

2 The timing of an irrigation will be determined by its place in a sequence of farming operations and may depart from the day on which D_1 is achieved by, say ±3 days, equivalent to ±10 mm of evaporation in a temperate climate.

3 A farmer is unlikely to know how much water he has applied to better than ±5 mm.

If the average interval between irrigations is 3 weeks, equivalent to 100 mm of evaporation, agricultural meteorologists can feel satisfied if their estimates of evaporation are correct to about ±15%. In Britain, this accuracy can be obtained by using the Penman formula as originally developed by MAFF for forecasting irrigation need. In a drier climate, where the Penman formula tends to underestimate evaporation from crops because the aerodynamic term is too small, the so-called Penman-Monteith formula can be used with a minimum surface resistance of 50 s m^{-1} to estimate a "potential" evaporation rate. Attempting to relate surface resistance to soil water deficit or water potential (Russell, 1980) is a difficult exercise, unlikely to benefit the farmer.

To sum up, progress in developing MORECS for agriculture and hydrology depends on a better understanding of soil and plant factors rather than a refinement in micrometeorology. Agricultural meteorologists need more information from the field about appropriate values of D_1 but hydrologists also need to know how surface resistance changes when D_1 is exceeded.

French, B K and Legg, B J, 1979. Rothamsted irrigation, 1964-76. *J. Agric. Sci., Camb.*, 92, 15-37.

Monteith, J L, 1981. Climatic variation and the growth of crops. *Q. J. Roy. Met. Soc.* 107, 749-774.

Penman, H L, 1971. Irrigation at Woburn VII. *Rep. Rothamsted Expt. Stat. for 1970*, part 2, 147-170.

Russell, G, 1980. Crop evaporation, surface resistance, and soil water statistics. *Agric. Met.*, 21, 213-226.

7 MORECS : NOTES ON A HYDROLOGIST'S PERSPECTIVE

K F Clarke, Operational Planning, Anglian Water Authority

Mr Clarke opened his presentation by stating that he would not necessarily give the view of a Hydrologist but rather that of a representative of the Water Industry. He described the operational planning work of Water Authorities and his job, within operational planning, at the Anglian Water Authority. Their objective was to make the most efficient use of the Authority's water resources.

Water Authorities have several uses for evaporation data: to assist flood forecasting; to assist water resource operation in drought periods; for calculations of groundwater recharge to assist in the planning of water resources development; and to give a guide to customers (eg. farmers) requiring such information.

An example of the use made of evaporation data at the Anglian Water Authority was illustrated by a description of the 'lumped' aquifer model of the Southern Lincolnshire Limestone, shown in Fig. 7.1.

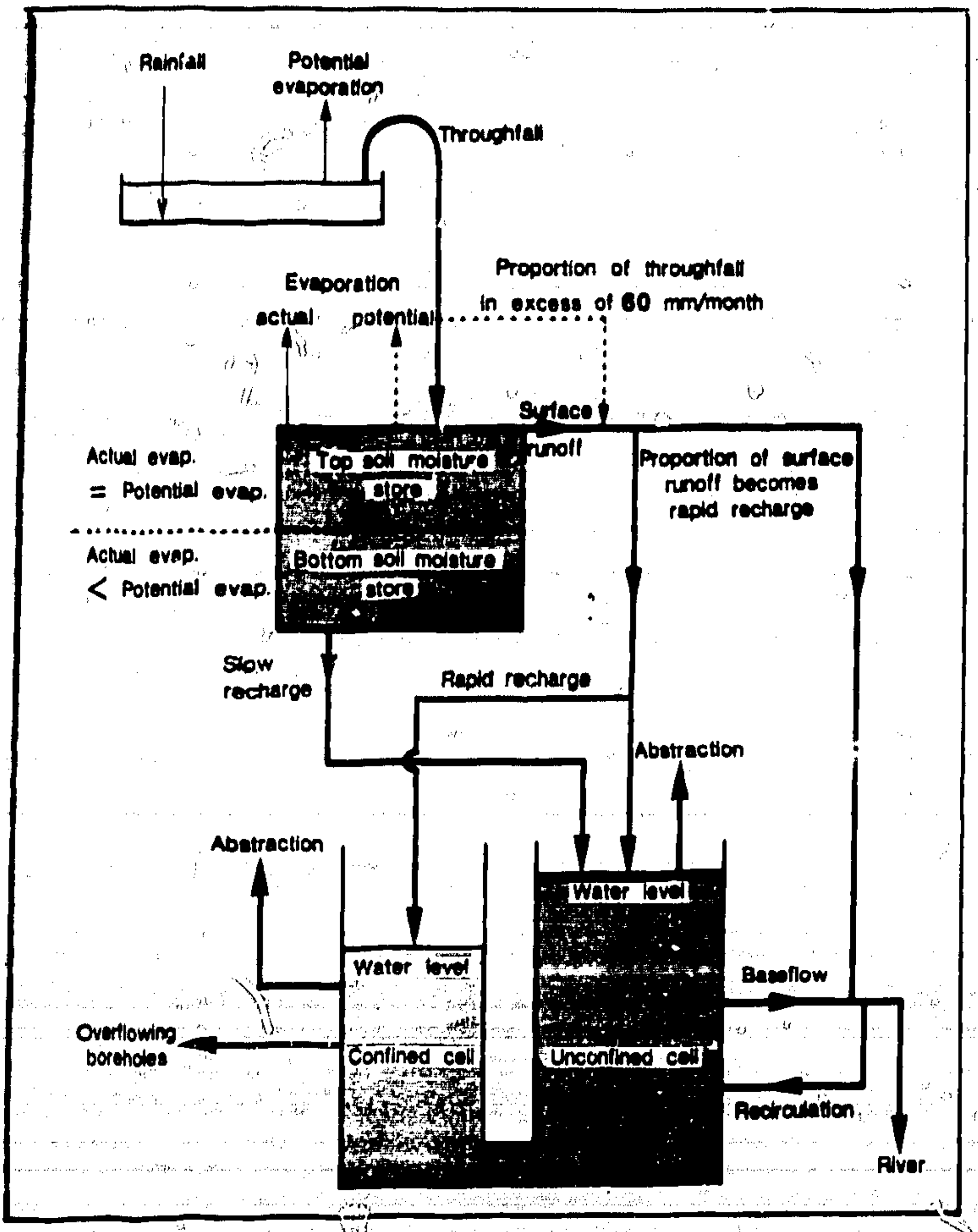


FIGURE 7.1

The 'lumped' aquifer model of the Southern Lincolnshire Limestone

Mr Clarke remarked that in his general opinion the data produced by MORECS had not been of much use to the Authorities. He considered that although MORECS calculates the meteorological component of the analysis well, it does not succeed in its treatment of the hydrological aspects. Thus it would appear that for many purposes the water authorities require MORECS evaporation information, plus a simple lumped model, which would be operated on a catchment basis.

8 COMPARISON OF FIELD DATA WITH WATER BUDGET CALCULATIONS

H S Wheater, Department of Civil Engineering, Imperial College of Science and Technology

Experience with the original Meteorological Office soil moisture model (Grindley 1967) and predominently clay soils under grass in the west of England, has indicated that comparison of the non-optimised model with observed soil moisture deficits can be excellent. In general the observed seasonal response is well reproduced (Fig. 8.1). Penman (1949) suggested that early season rainfall would influence root development and hence the effective root constant, eg dry conditions would encourage deeper rooting. It may not be coincidence that the best performance of this model compared to field observations was achieved for 1977 in which year the early season rainfall was close to the "typical" conditions which influenced Penman's original choice of root constant. This might indicate that a dynamic plant representation would usefully improve the performance of this type of model.

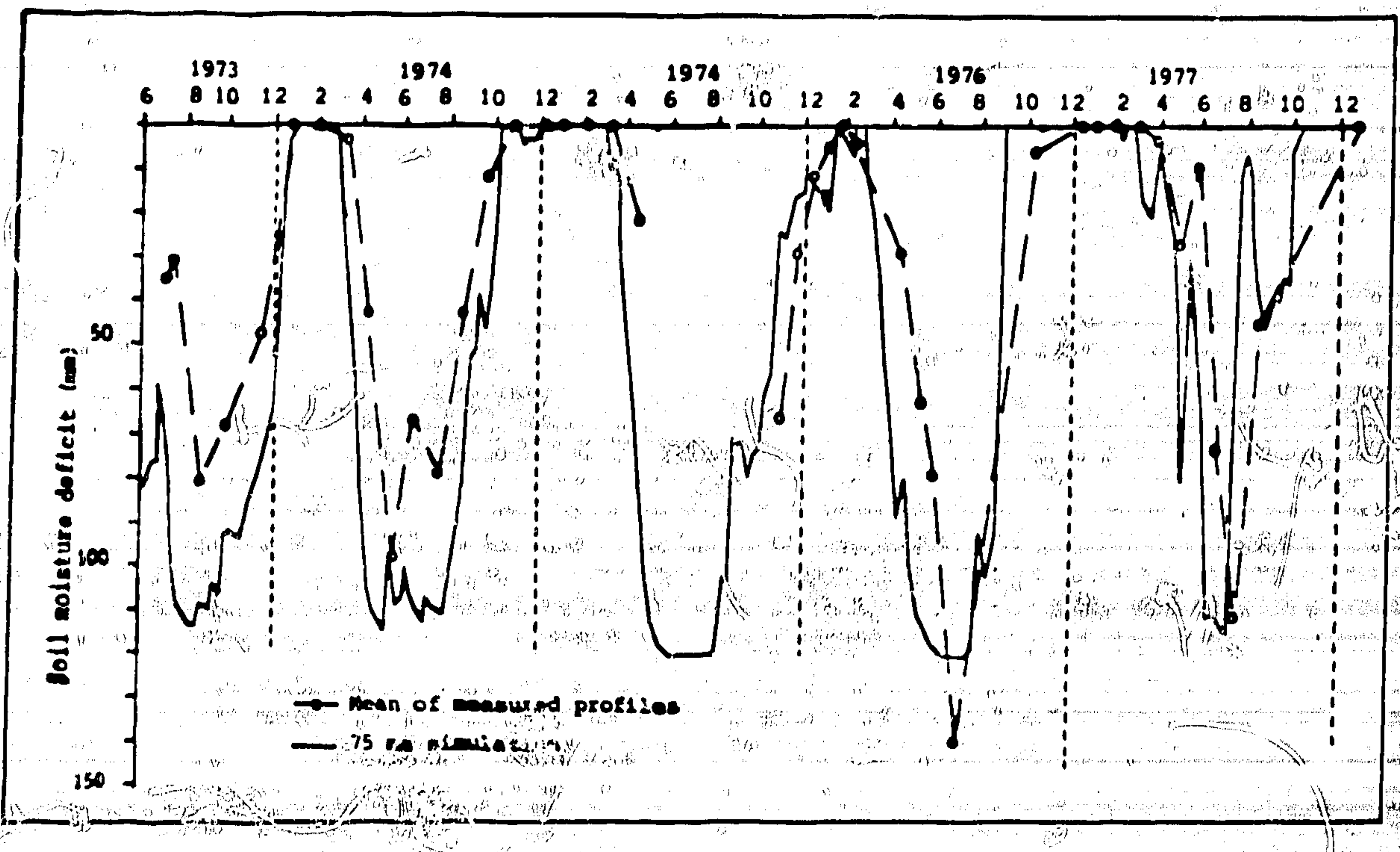


FIGURE 8.1 Comparison of SMD estimates prepared using the Grindley model, with SMDs measured at six sites near Gloucester in predominently clay soils under grass

Some discussion has taken place of the sensitivity of models to the accuracy of the potential evaporation and rainfall data used when regional estimates are required. A sensitivity analysis of the Grindley model demonstrates that the introduction of 10% errors to potential evaporation and rainfall data has a much smaller effect on the calculated regional soil moisture deficit than the accurate description of land use distribution (Fig. 8.2).

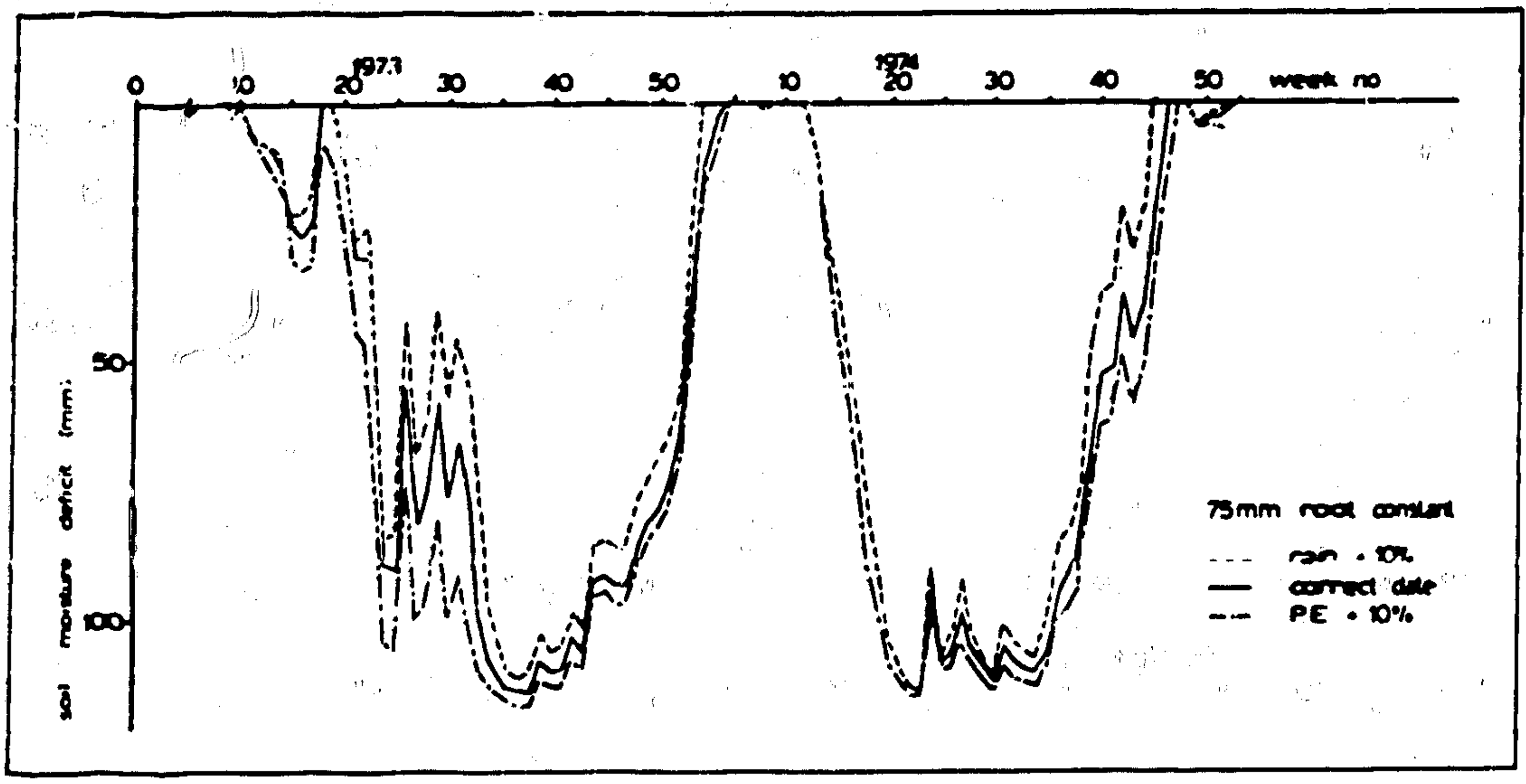


FIGURE 8.2 The sensitivity of the Grindley model for SMDs under grass to the meteorological data input

High quality soil moisture data to compare with estimates from models such as MORECS are comparatively scarce, particularly for vegetation other than grass. For this reason a series of experiments has been established at the Imperial College Field Station, Silwood Park, in which soil moisture conditions under grass, cereals, orchard, brassicas and field beans are being monitored over a three year period.

Preliminary results for the 1980 season indicated that MORECS significantly overestimated soil moisture deficit for the crops listed above on a sandy soil of low available water capacity.

Grindley, J 1967. The estimation of soil moisture deficits. Met. Mag. Lond, 96, 97-108.

Penman, H L , 1949. The dependence of transpiration of weather and soil conditions. J. Soil. Sci. 1, 74-89.

9 ESTIMATION OF SOIL MOISTURE EXCESS, AND VERIFICATION

B J Greenfield, Thames Conservancy Division, Thames Water Authority

Hydrological interest in soil moisture models lies usually in the estimation of soil moisture excess, i.e. percolation or runoff. It is important therefore, to consider soil moisture excess rather than deficit, when assessing the performance of a soil moisture model since the generation of apparently reasonable deficits does not ensure the generation of reasonable estimates of excess.

One method of testing estimates of soil moisture excess is to use a catchment storage model and to compare generated and observed river flows. Although it is generally undesirable to use one model to test another there is no more direct method and it is probably as valid as using point measurements of soil moisture deficit to test calculated areal values.

Direct summer percolation

It can be shown, using this method, that the drying curve concept can produce reliable estimates of soil moisture excess provided one basic modification is made to the model and provided an appropriate drying curve is used. It is not sufficient to arbitrarily define a drying curve and then to expect reliable results. The basic deficiency in the traditional (Penman) approach is the absence of summer percolation. There is widespread acceptance of the existance of this phenomenon, (e.g. from groundwater level and river flow hydrographs and from tracer experiments) but it is often, as in MORECS, totally ignored in soil moisture models. A simple allowance of say 15% of rainfall excess over potential evaporation on any day by-passing the soil moisture store is usually sufficient to provide the right order of summer percolation. Figure 9.1 shows the effect of making this allowance on a generated river flow hydrograph.

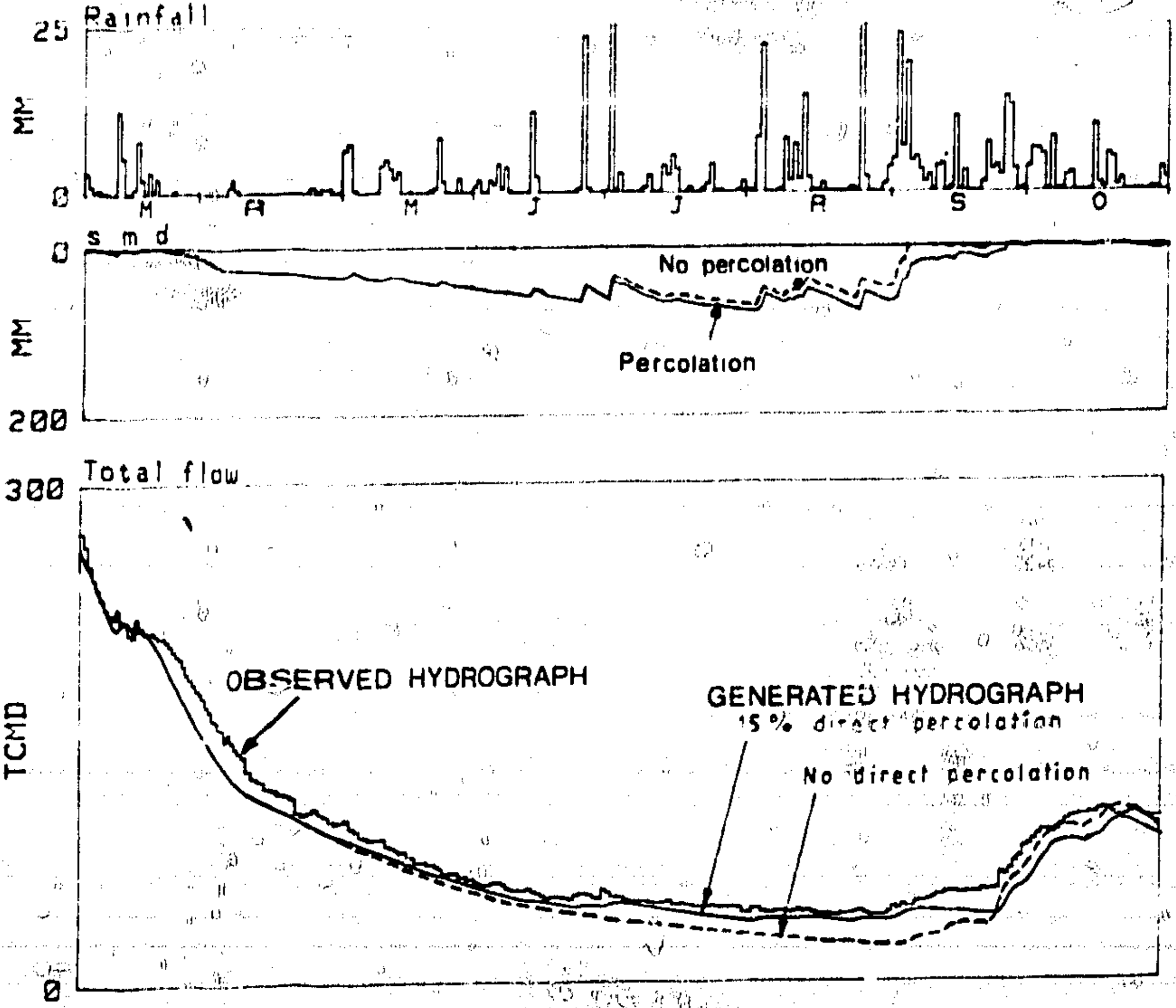


FIGURE 9.1

River Coln at Bibury 1974

Direct percolation 1974

The optimum drying curve

The groundwater model approach may be extended to provide estimates of seasonal maximum actual deficit which in turn may be used to derive the optimum drying curve slope and "root constant" for a specific application. Figure 9.2 shows an example of determining actual soil moisture by trial and Figure 9.3 shows how such estimates may be used to derive a drying curve.

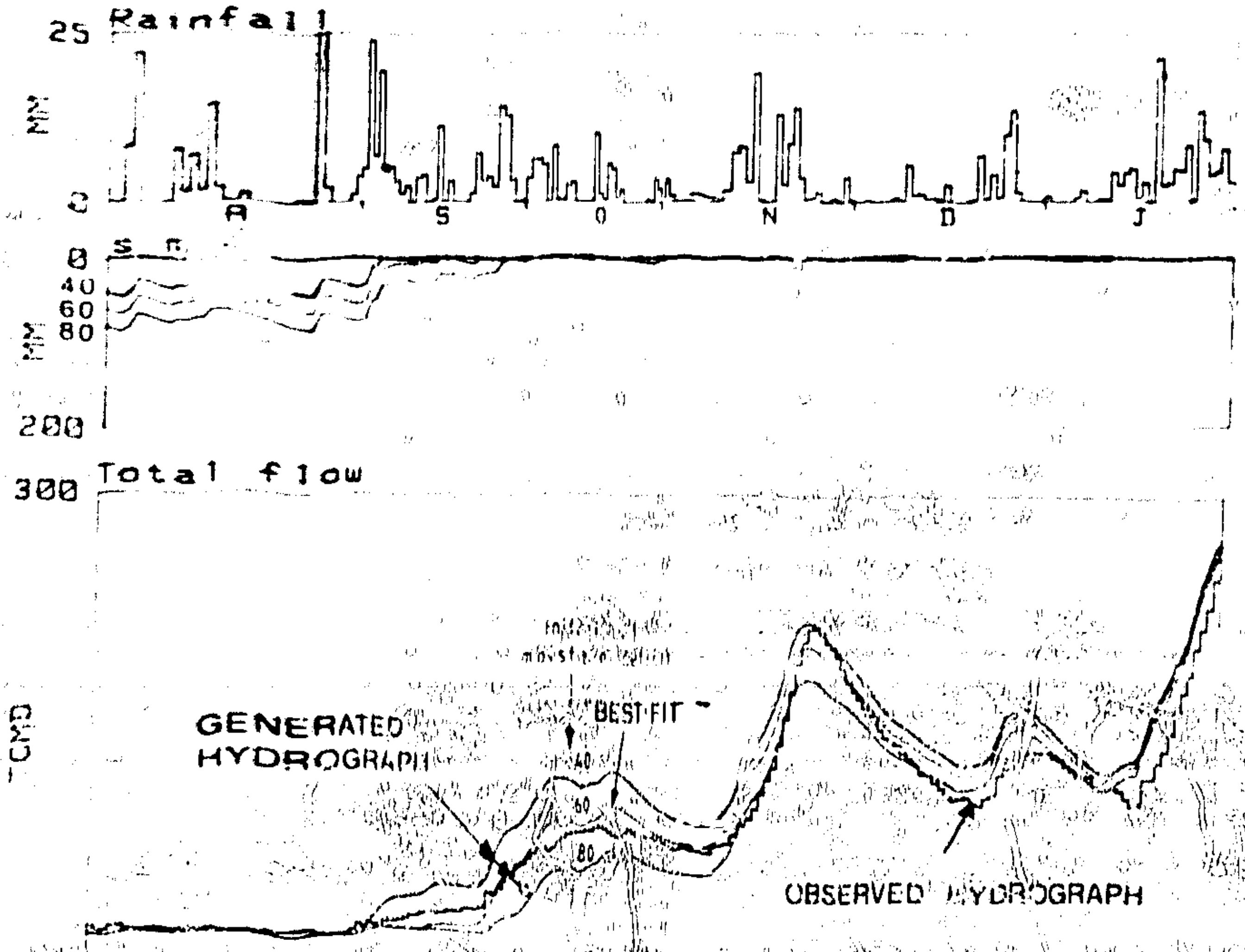


FIGURE 9.2

River Coln at Bibury 1974

Estimating actual deficit

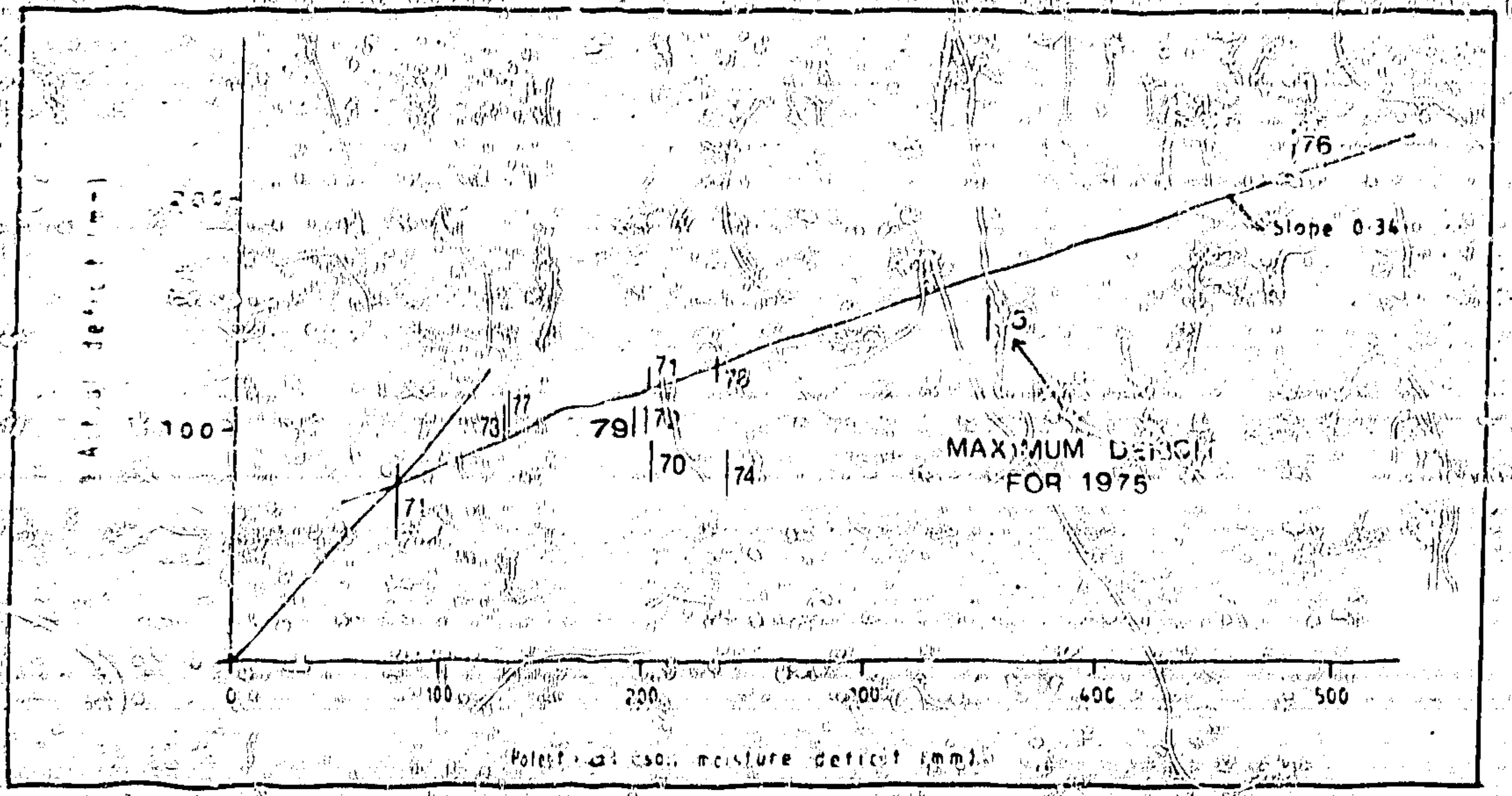


FIGURE 9.3 Derivation of drying curve. **River Enborne surface runoff**

At Thames Water we have found the root constant value for grassland varies from 25 mm to 75 mm according to underlying geology, but the drying curve slope (i.e. actual/potential evaporation ratio for deficits greater than the root constant) has a constant value of approximately 0.3 for all areas. Deficits apparently attained in 1976 indicate that there is no validity in the concept of maximum deficit or at least that any maximum is beyond the range of deficit that is likely to occur. It is not clear where the concept of maximum deficit originated, the author is not aware of any reference to the idea in Dr Penman's publications. Figure 9.4 shows examples of derived drying curves for grassland compared with Penman's grassland curve.

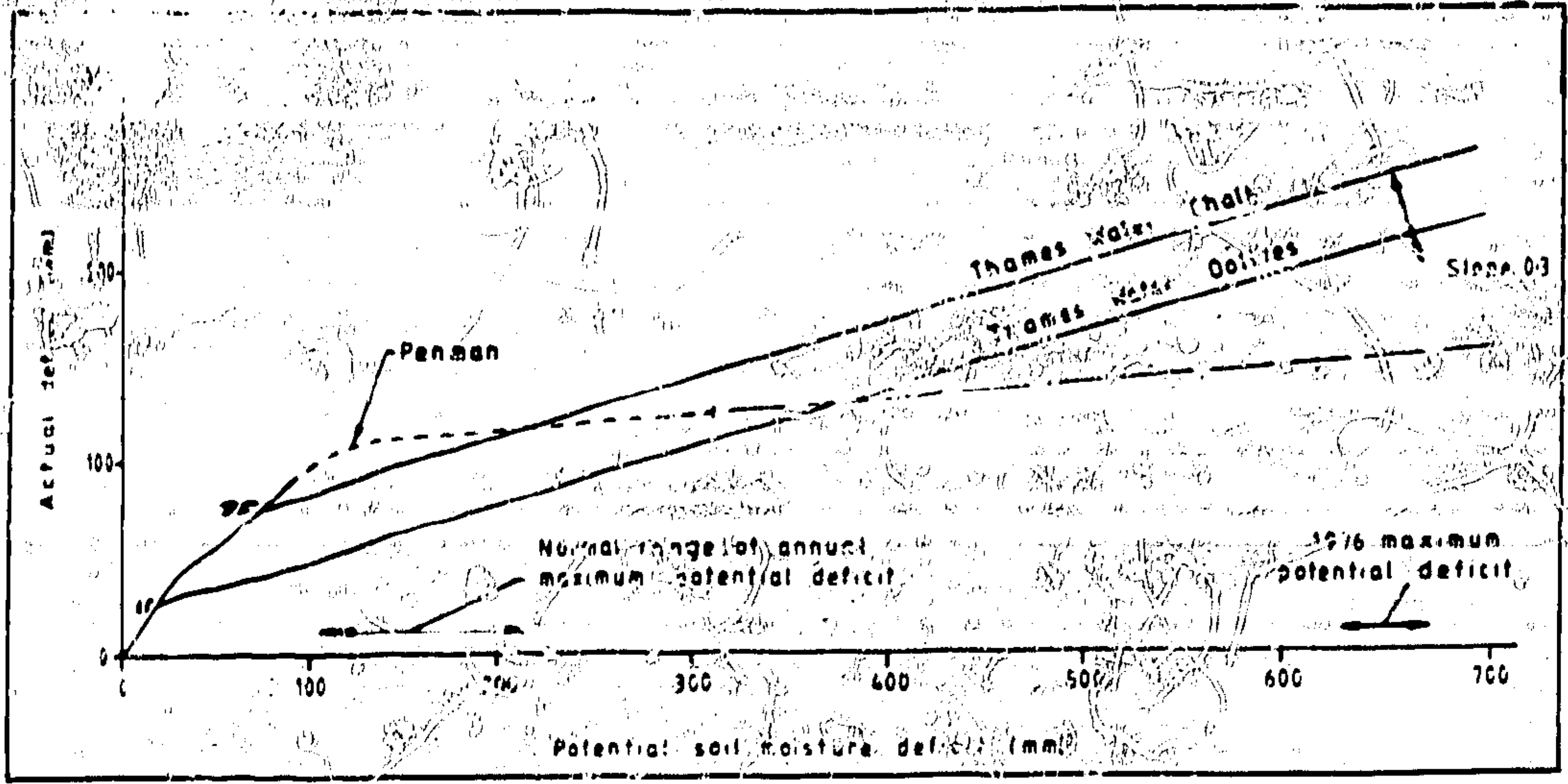


FIGURE 9.4 Drying curves for grassland

10 COMPARISON OF MORECS WITH CATCHMENT DATA

G Davies, Severn Area Unit, Severn-Trent Water Authority

During the autumn of 1980 some doubt was cast on the accuracy of soil moisture deficit (SMD) data produced by the MORECS system for the Severn Catchment. Moderately high values of SMD were reported for much of the Severn basin for a period when river flows were responding to rainfall implying that the catchment was near to field capacity.

It was therefore decided to compare MORECS data with data for a natural catchment with little groundwater storage for the period January 1979 to December 1980. The Rea Brook (catchment area 178 km^2), a tributary to the River Severn in Shropshire, was chosen as a suitable catchment with a good flow measurement station. A network of five daily raingauges and one automatic climate station (located 20 km to the north) was used to calculate daily areal rainfall and Penman potential evaporation data. The catchment falls partly in the west of MORECS square 124, which was used for comparison.

A computer program was used to calculate daily catchment estimates of actual evaporation, soil moisture deficit and effective rainfall using the root constant concept and using Penman drying curves and keeping an independent budget for each land use type in a similar way to the method published by the Meteorological Office (Grindley 1969). The catchment land use distribution was estimated by observation and local knowledge.

Water balance Data Comparison

	1979		1980	
ANNUAL TOTALS (Units - millimetres)	MORECS Square 124	Rea Brook	MORECS Square 124	Rea Brook
Rainfall	814	755	816	860
Potential Evaporation (Grassland)	576	513	656	500
Actual Evaporation (Real Land Use)	538	439	572	461
Effective Rainfall	256	316	248	399
Rainfall minus Actual Evaporation	276	316	244	399
Runoff	-	324	-	394

Discussion of results

Annual totals of potential evaporation as calculated by MORECS were significantly higher than the catchment estimates, by 12% in 1979 and 31% in 1980. In 1980 MORECS values were greater for every month (Fig. 10.1). Similarly MORECS estimates of actual evaporation were higher by 22% in 1979 and 24% in 1980.

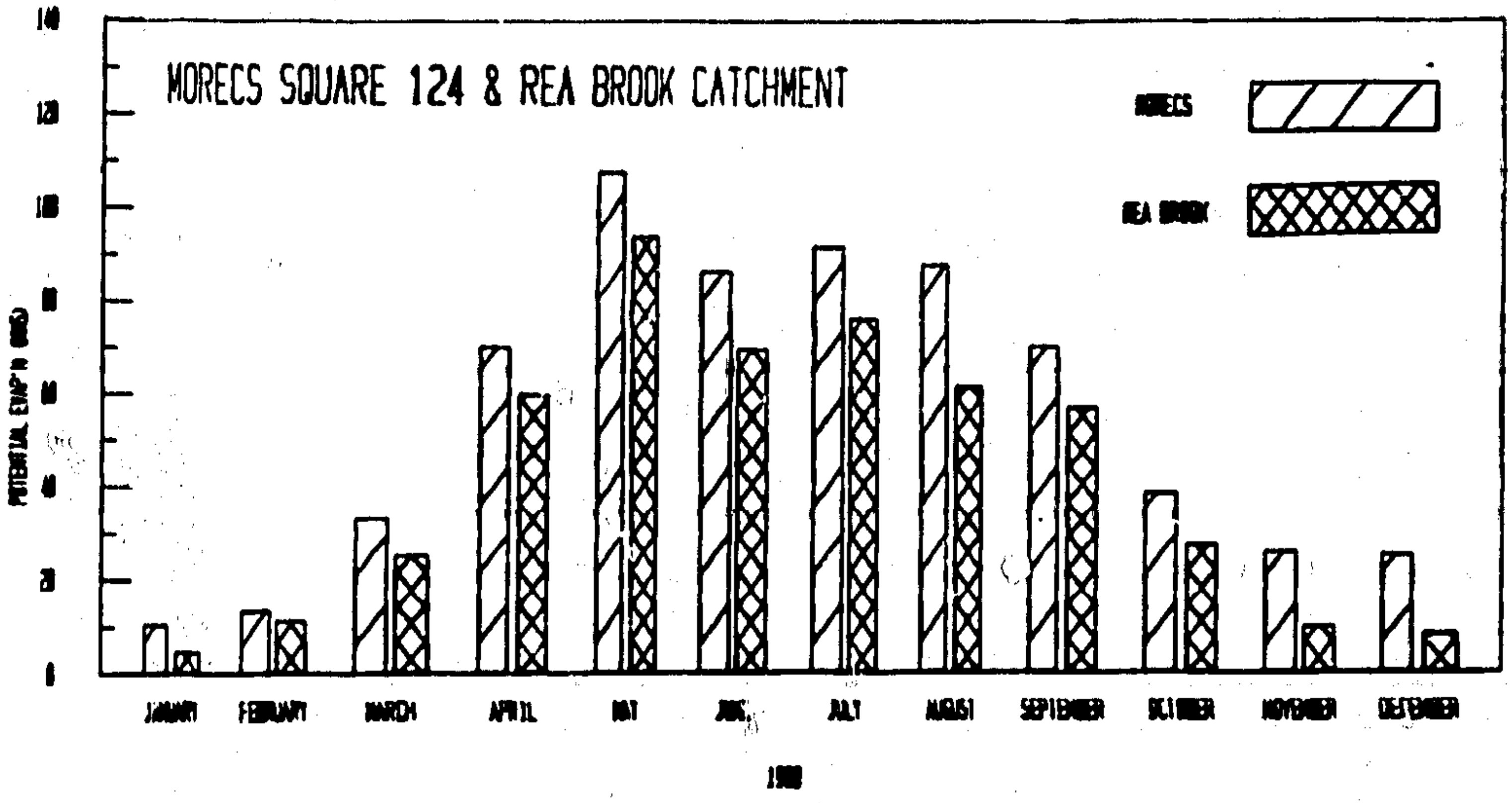


FIGURE 10.1 **MORECS estimates of potential evaporation for square 124, and values for the Rea Brook catchment in 1980**

In 1979 MORECS estimates of SMD returned to field capacity slightly later than the catchment values. However in 1980 MORECS values were significantly higher from June onwards, not reaching zero by the end of December (Fig. 10.2), whereas the SMD for the Rea Brook catchment returned to field capacity during October.

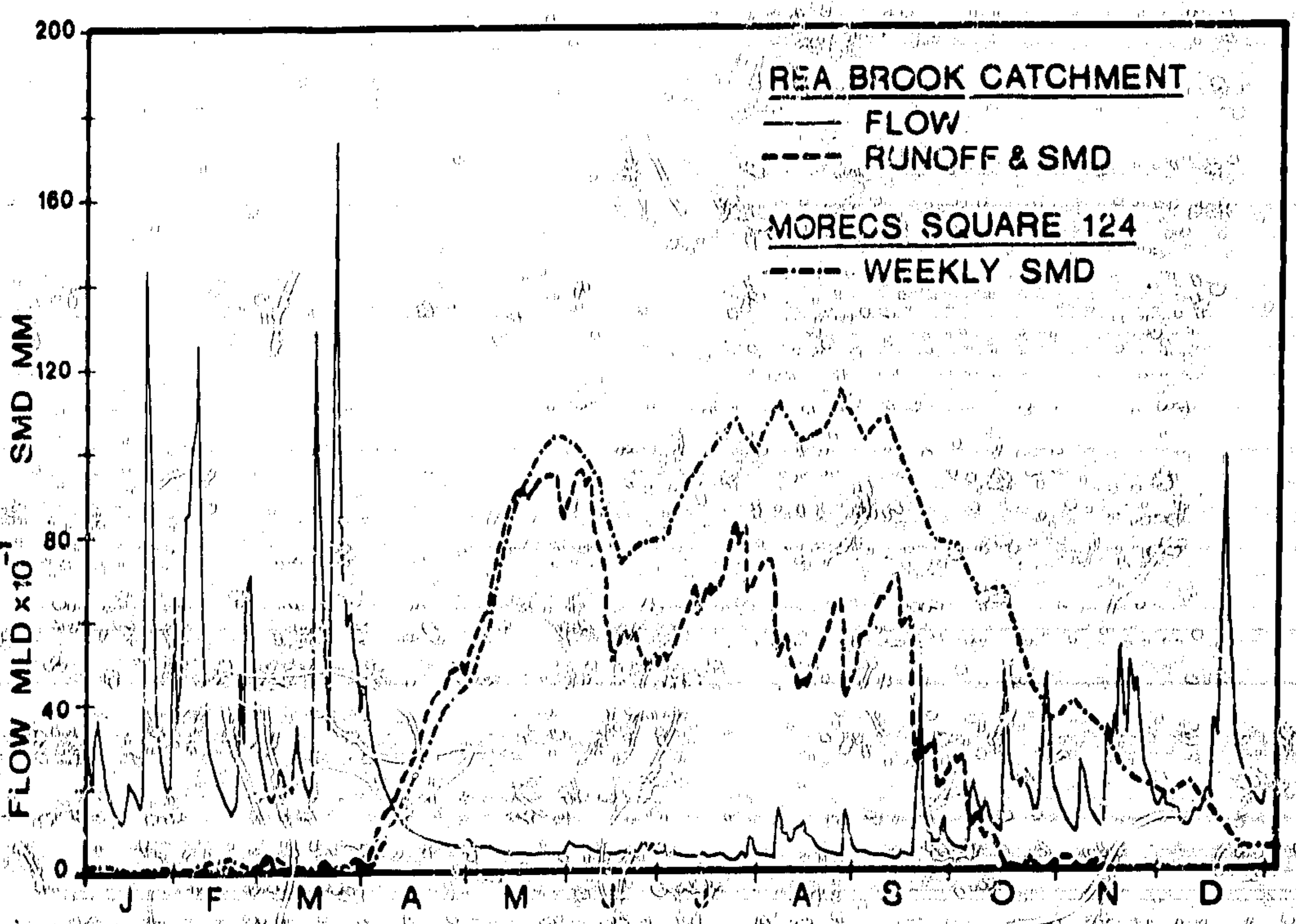


FIGURE 10.2 **Comparison between MORECS SMD estimates and values for the Rea Brook catchment in 1980**

Examination of the flow hydrograph for the Rea Brook shows that it started to respond to rainfall in late September to early October.

MORECS estimates of effective rainfall were significantly lower than the catchment values, by 19% in 1979 and 36% in 1980. Values of catchment runoff for both years agree very closely with the catchment estimates of effective rainfall.

Conclusions

Because the estimates of catchment effective rainfall agree closely with the values of runoff and also the catchment SMD returns to field capacity when the flow hydrograph starts to respond directly to rainfall, it seems reasonable to accept the values of actual and potential evaporation for the catchment. Doubt is therefore expressed on the accuracy of the potential evaporation data quoted for MORECS square 124, particularly for 1980 when greater differences were observed.

This simple study illustrates the use that can be made of river flow data to check catchment estimates of SMD and effective rainfall. Effective rainfall data are used by the Water Authority to estimate the recharge to groundwater, therefore it is important to have a means of validation. When the final version of MORECS has been developed it would be valuable to run the model using quality controlled data from the Meteorological Office archive for selected catchments over a period of approximately twenty years in order that a comparison can be made against runoff data.

Grindley, J. [illegible]. The Calculation of Actual Evaporation and Soil Moisture Deficit Over Specified Catchment Areas. Hydrological Memorandum 38, Meteorological Office, Bracknell.

DISCUSSION

Chaired by R N Crossett — Collated by C M K Gardner

The main discussion took place at the end of the meeting. However several comments were made in the course of the morning session of submitted papers and these are reported first.

Morning session

Surface resistance values

H S Wheater asked whether much information was available on the relationship between soil moisture deficit and surface resistance values. N Thompson replied that there were few published data available but it was possible to use soil moisture deficit and potential evaporation data to calculate surface resistance values.

Calculation of potential and actual evaporation

H L Penman requested that the meeting should not use the term evapotranspiration in place of evaporation and transpiration and pointed out the peculiar nature of the term soil moisture deficit, it being a measure of something which is not there! Referring to the Penman-Monteith equation used in MORECS, he stressed that the emissivity term was not necessary and should be omitted. Concern was expressed at the very simple relationship of the Ea:Ep ratio to depletion of the available soil water reservoir used in MORECS. And, he reminded the meeting, quite a lot of information concerning limiting deficit values had been generated in the course of the Woburn and Rothamsted irrigation experiments (Penman 1971 French *et al.* 1973).

N Thompson agreed to not use the term evapotranspiration and acknowledged the difficulties of the soil moisture deficit concept! He explained that the simple straightforward relationship between Ea:Ep and SMD had been adopted for use in MORECS in the absence of firm evidence to suggest that another would be more appropriate.

Field capacity

S Le Grice expressed surprise that the model used by MORECS to represent soil moisture extraction still assumed that drainage could only take place when the soil moisture content returned to field capacity; this particularly ignored the existance of cracking soils. Referring to J P Bell's paper (page 15) he suggested that the two situations in which "true" field capacity conditions would occur (ie in freely draining soils with a shallow groundwater table or in soils of low unsaturated hydraulic conductivity) could apply to a large part of the agricultural land in this country.

H L Penman referred to the work of Emerson (1955) which demonstrated that clay soils do not return to the same "field capacity" moisture content each winter. The maximum water content achieved in winter by a clay soil depends on its degree of recovery from shrinkage during the previous summer. He concluded that should one have to define a field capacity moisture content, "Do your best"!

J P Bell stressed that to make a valid comparison between measured deficits and estimates derived from meteorological data, field capacity must be a physically real state; as discussed in his paper, this is only so in certain restricted circumstances. By modifying the field capacity values used in the comparison described earlier, it was possible to improve the fit of MORECS to the measured deficits. However such improvements could not be justified unless there was good reason to doubt the original field capacity value.

Soil profile depth and user requirements

C V Smith commented that MORECS attempted to serve two distinct customers, the Agriculture and the Water Industries. The system had been initially designed to suit the needs of agriculturists who are interested in the top layer of the soil profile and use soil moisture deficit information primarily as a guide to irrigation requirements. For this purpose it is probably adequate to consider a soil profile of 1.5 m depth whereas hydrologists are probably interested in the whole of the upper part of the soil/unsaturated zone, ie a layer of perhaps 12 m depth. However, as yet MORECS had not been designed to allow for moisture changes at such depths. It would be useful if the amount of water moving across the base of the soil profile as drainage and upward fluxes, described by J P Bell (page 15) could be quantified. In particular he wondered whether the quantities were similar to, or greater than, rainfall additions during the summer period.

MAIN DIS[illegible]

The Chair[illegible] lead the discussion and he did so by suggesting that ther[illegible] [illegible]nique of providing information:

What [illegible]
Wh[illegible] [illegible]ptable?

Another point [illegible]der would be the economics involved in providing the solution but in the present context this was not so relevant. The Meteorological Office required a clear idea as to how the soil moisture deficit information that they produced would be used, and in particular, as to what accuracy was desirable. Presumably estimates within 10 mm of the measured values would be very satisfactory but what lower degree of accuracy would be acceptable?

Requirements of flood hydrologists

The view of flood hydrologists was explained by J V Sutcliffe. They require soil moisture deficit information as an index of the quantities of run-off likely to result from given rainfall events. It is also needed to relate the statistical probability of given floods to rainfall statistics. In the course of the Flood Study (NERC 1965) it was found that antecedent soil moisture conditions were the most important factor in flood prediction. Thus while it is important to have real-time estimates of soil moisture deficit for flood warning purposes, the length of consistent soil moisture record is as important as accuracy in studies of flooding probability.

N Thompson commented that it was recognised that MORECS could be more useful if estimates of negative deficits during winter months were provided in addition to the current output. These would be of use to both the farmer and the hydrologist. Also, it should be possible to incorporate a crude model to allow for drainage from the lower part of the profile, so making MORECS more attractive to hydrologists.

Agroclimatic areas

A suggestion that a more acceptable solution to the problem of MORECS accuracy might arise if the estimates were related to agroclimatic areas, was put by S Le Grice. The agroclimatic areas were defined as a result of discussions between members of the Meteorological Office and the Agricultural Advisory and Development Service (ADAS) and each is as uniform as possible in farming practice and climatic characteristics (Smith and Trafford 1976). C V Smith asserted that it was much simpler for the computer program to use a basis of regular grid squares. N Thompson pointed out that MORECS was not only intended for use by the agricultural community, but should also serve the water industry; the use of grid squares was a compromise between their different needs. However, S Le Grice went on to suggest that as topography had been very significant in influencing the definition of the agroclimatic areas, there was likely to be a coincidence between their boundaries and those of the water authorities' catchments. Indeed interpolation of synoptic data over agroclimatic areas rather than grid squares should be simpler because of their inherent homogeneity. N Thompson agreed with the latter point but noted that upland areas, due to the absence of meteorological stations, would always be difficult to deal with. Also while the boundaries of the agroclimatic areas are precisely defined the spatial resolution of MORECS deficit estimates are not so fine.

Causes of disagreement between MORECS and measured SMD values

J C Rodda emphasised the need for systematic studies to evaluate systems such as MORECS. The data presented to the meeting had demonstrated discrepancies between measured deficits and MORECS estimates which the speakers had been tempted to explain principally in terms of the potential evaporation estimate so ignoring other possible sources of error. These might include errors in the calibrations used for the neutron probes with which the soil moisture data were measured, the poor representation of soil heat flux in the calculation of potential evaporation, or the underestimation of rainfall arising from the use of standard rather than ground level gauges.

C M K Gardner stated that in the comparison described earlier the neutron probe data had been converted to moisture contents using the standard calibrations derived at the Institute of Hydrology (Bell 1976, Gardner 1981). This approach had been adopted for the contributors to the soil moisture databank had used several different methods to calibrate their neutron probes.

Variation in potential evaporation

I R Calder's concluding remark (page 32) which inferred that the spatial and temporal variation of potential evaporation was small in Britain was questioned by J C Rodda. I R Calder explained that his work had demonstrated that in terms of their use in soil moisture extraction models, potential evaporation values apparently vary little. It is probable that this occurs because feedback mechanisms in plants limit transpiration losses when there is a high evaporative demand. Consequently simple models which do not allow for such factors can predict soil moisture deficits more satisfactorily if conservative potential evaporation values are used.

Other methods for evaluating MORECS

J C Rodda also reminded the audience of the lysimeter work conducted by F H W Green (Green 1962) and suggested that the data would be suitable for the checking of MORECS soil moisture deficit estimates. The suggestion that it would be worthwhile to conduct a comparison between the estimates of hydrologically effective rainfall prepared by MORECS, and actual run-off measured as streamflow, was put by A Gustard. Such a comparison could be made throughout the country. R D Hey commented that it would be useful to distinguish between comparisons with MORECS values representing grid squares for which meteorological data are used from stations within the squares, and those representing squares for which the meteorological data are interpolated from elsewhere.

N Thompson agreed that both lysimeter and river gauge data could be used to verify MORECS. However caution was required when dealing with data from lysimeters for they are prone to be unrepresentative. Neutron probe data had been used in preference to stream flow data as they were more readily available and easier to use.

Importance of soil factors

Explaining that he had used lysimeter data to check soil water budget models (Parkes and O'Callaghan 1980), M E Parkes stressed that the soil factors were more important than the potential evaporation calculation in such models, as I R Calder's paper had also indicated. To overcome the problem of the definition of field capacity which J P Bell had outlined, a dynamic concept of available water capacity was required.

A D Hughes expressed concern that the meeting was omitting to understand reality, (ie what happens in a field soil) in its attempts to explain how models function.. For example, it is possible to induce changes in transpiration rates by using sub-soil cultivation techniques (Goss *et al.*, 1978; Rowse, 1980); on some soils such cultivation increases the supply of water to the crop. He asked whether it would be possible to use the soil moisture databank to investigate this effect. C M K Gardner replied that as much of the soil moisture databank represented permanent pastureland little of the data would be suitable for such an investigation.

Root Constants

M McGowan commented that the root constant for the same species growing on the same soil could differ, and referred to a study of 3 consecutive crops of winter wheat (var Maris Huntsman) grown in the same field at the Nottingham University Farm, Sutton Bonington. In 1975 the crop transpiration rate remained close to the potential value until about 67% of the available water has been used. In the second drought year 1976 the ratio of actual to potential evaporation fell below 1 after only 50% available soil water had been depleted. This difference between crops was not due to different weather conditions but resulted from the differing abilities of the crops to maintain turgor. As the soil dried out the 1975 crop made a significant osmotic adjustment, hence was able to maintain turgor and stomatal opening until a large deficit has developed. The 1976 crop hardly made any osmotic adjustment, hence lost turgor early in the season with consequent early closure of stomata. Clearly the surface resistance is not uniquely related to soil water deficit and amongst other factors the physiological control of plant turgor must be considered.

[In 1977, because of frequent light showers, a reduction in transpiration rate below the potential value was not evident until 80% depletion of available water].

Surface resistance and soil moisture deficits

J S Wallace emphasised that surface resistance (r_s) is not a unique function of soil moisture deficit and so care should be taken when attempting to relate the two. r_s depends on leaf area and stomatal resistance but it is through its indirect effect on stomatal resistance that soil moisture deficit influences r_s. However, other factors also affect stomatal resistance including radiation, vapour pressure deficit and plant water status (eg Jarvis 1976). Furthermore, it is soil moisture potential, not deficit, which plants "sense". Although different soils may have the same deficit, the potential of the water in those soils may be quite different. For the operational purposes of MORECS, it was doubtful whether the increased complexity in the new evaporation model (arising from trying to use r_s) was desirable, or would necessarily give a better estimate of evaporation than simpler models such as those described by I R Calder.

N Thompson recognised that the soil moisture deficit - r_s relationship was not a simple one but the new version of MORECS would allow for changes in leaf area index.

Field factors

A K Smith-Carrington remarked that the discussion had focussed on the vertical movements of soil water and ignored lateral movements which could be very important. She suggested that differences in soil moisture deficit due to topography alone could be substantial and questioned attempts to represent 40 x 40 km grid squares with a single deficit value.

Irrigation scheduling

Referring to field experiments undertaken in East Anglia, (Scammell and Hey 1976; Dent *et al* 1978), R D Hey reported that the correct timing of irrigation applications could considerably improve crop yields. Two systems for indicating irrigation requirement had been compared for a crop of cabbages. These were the A D A S system, whereby deficits are estimated from meteorological data, and one based on measuring soil moisture tensions; irrigation water was applied when tensions exceeded 0.7 bar. The tensiometer system was very effective in terms of yeild and water use. The water balance approach over-irrigated, giving excess drainage, and also allowed water stress to develop between irrigations. It was doubtful whether using MORECS-type systems one could ever produce results comparable to those with the tensiometer system.

MORECS improvement

A Papaioannou noted that work conducted by the Anglian Water Authority corroborated the finding that MORECS currently over-estimated soil moisture deficit. Usually few measured soil moisture data were available to water authorities and so there was much scope for the MORECS system if its accuracy could be improved. From the preceeding discussion it appeared that the wherewithall to make improvements was available.

Limitations on MORECS improvement

N Thompson remarked that the Meteorological Office staff were aware that the MORECS system was currently not as good as it might be but some of the ideas for improvements to it which had been put forward were rather optimistic. The system could not be greatly enlarged to include all the options which had been suggested because of limitations on both computing costs and the quantity of data output.

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MORECS DISCUSSION MEETING

Friday [illegible] April 1981.

PROGRAMME

The meeting will be chaired by Dr R N Crossett of the Chief Scientists Group, Ministry of Agriculture, Fisheries and Food.

10.00 am	Introduction and welcome - Chairman
10.15 am	MORECS - Dr N Thompson (Meteorological Office)
11.00 am	Coffee
11.15 am	The soil moisture abstraction model used by MORECS - Dr C M K Gardner (IH) Problems of 'field capacity' and 'soil moisture deficit' in the context of MORECS and similar models - J P Bell (IH) Preliminary comparisons between MORECS and measured soil moisture deficits - Dr C M K Gardner (IH) The prediction of soil moisture deficit: an operational approach - Dr I R Calder (IH)
1.00 pm	Lunch
2.00 pm	MORECS: an agricultural perspective - Professor J L Monteith (Department of Environmental Physiology, University of Nottingham)
2.30 pm	MORECS: a hydrologists' perspective - Mr K F Clark (Resources Planning Directorate, Anglian Water Authority)
3.00 pm	Concluding discussion
4.00 pm (approx)	Tea

List of Delegates

M Ali	Civil Engineering, Univ. Newcastle upon Tyne
A C Armstrong	Field Drainage Experimental Unit, Cambridge
R A Arrowsmith	Field Drainage Experimental Unit, Cambridge
D Atkinson	East Malling Research Stn., Kent
M Ayles	Meteorological Office, Bracknell
I Barrie	Meteorological Office, Bracknell
J P Bell	I H
P G Biddle	Tree Conservation Ltd., Wantage
R D Blackwell	Plant Breeding Institute, Cambridge
D B Boorman	I H
G A Burrow	Southern W A, Worthing
I R Calder	I H
G Chubb	Severn Trent W A, Nottingham
K F Clark	Anglian W A, Huntingdon
R T Clarke	I H
J D Cooper	I H
F Cope	Fisons Ltd, Levington Research Stn, Ipswich
R N Crossett	Chief Scientist's Group, Ministry of Agriculture, Fisheries & Food, London
G Davies	Severn-Trent W A, Malvern
D Evans	Anglian W A, Boston
M Field	Meteorological Office, Bracknell
G Fry	U [illegible] G Consultants Ltd, Warwick
C M K Gardner	I H
C Glenny	Thames W A, Reading
R Goodhew	Severn Trent W A, Malvern
F H W Green	I H
B J Greenfield	Thames W A, Reading
J Grindley	Meteorological Office, Bracknell
H M Gunston	I H
A Gustard	I H
R J Harding	I H
P D Hedges	Civil Engineering Univ. of Aston
R D Hey	Environmental Science, Univ of East Anglia
M G Hodnett	I H
K R Howse	Letcombe Laboratory, Oxfordshire
A D Hughes	South-West Region, ADAS
M W Huxley	Long Ashton Research Stn, Bristol
P Innes	Plant Breeding Research Stn, Cambridge
W Jenkins	Letcombe Laboratory, Oxfordshire
J R Jones	West Midland Region, ADAS, Wolverhampton
S Le Grice	Field Drainage Experimental Unit, Cambridge

J A Mawdsley	Civil Engineering, Univ of Newcastle upon Tyne
B May	Meteorological Office, Bracknell
J S G McCulloch	I H
M McGowan	Environmental Physiology, Univ of Nottingham (Sutton Bonington)
J L Monteith	Environmental Physiology, Univ of Nottingham (Sutton Bonington)
C E Mullins	Soil Science, Univ of Aberdeen
D B Naysmith	Agriculture, Univ of Edinburgh
S Nwabuzor	Civil Engineering, Imperial College, London
A Papaioannou	Anglian W A, Boston
M E Parkes	East of Scotland College of Agriculture, Edinburgh
H L Penman	Formerly Rothamsted Research Stn, Harpenden.
L Persson	Univ of Upsala, Sweden
K Powell	Anglian W A, Boston
S J Richardson	West Midland Region, ADAS, Wolverhampton
J C Rodda	Water Data Unit, Reading
B E Ryden	Univ of Upsala, Sweden
D Sherratt	Civil Engineering, Imperial College, London
C V Smith	Meteorological Office, Bracknell
A K Smith-Carrington	Institute of Geological Sciences, Wallingford
J B Stewart	I H
J V Sutcliffe	I H
C Thomas	East Malling Research Stn, Kent
N Thompson	Meteorological Office, Bracknell
J S Wallace	I H
S R Wellings	I H
J D Wheater	Fisons Ltd, Levington Research Stn, Ipswich
H S Wheater	Civil Engineering, Imperial College, London
T R Wood	Severn Trent W A, Birmingham