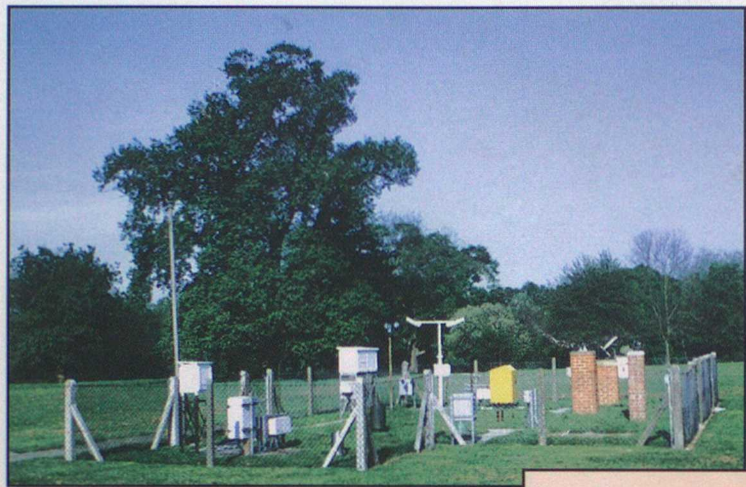
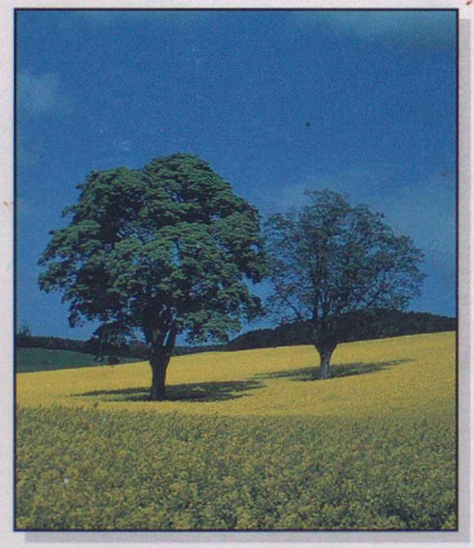
The Meteorological Office Rainfall and Evaporation Calculation System

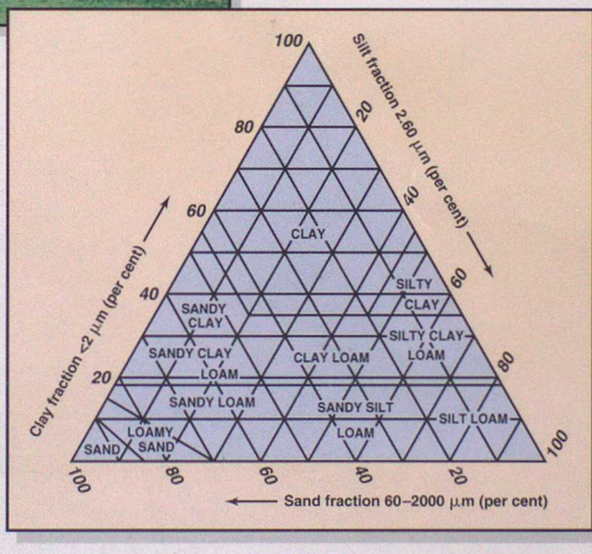
MORECS version 2.0



WEATHER



LAND USE



SOILS

An update to
Hydrological Memorandum 45

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THE METEOROLOGICAL OFFICE RAINFALL AND EVAPORATION CALCULATION SYSTEM: MORECS VERSION 2.0 (1995)

by

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An update to Hydrological Memorandum 45

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The Meteorological Office Rainfall and Evaporation Calculation System: MORECS version 2.0 (1995)

1. Introduction

MORECS (an acronym for Meteorological Office Rainfall and Evaporation Calculation System) was introduced in 1978 as an eventual replacement for the Estimated Soil Moisture Deficit (ESMD) bulletin first issued by The Met. Office about 15 years earlier. MORECS underwent an extensive revision in the winter of 1980/81 and the version which was introduced in summer 1981 continued virtually unchanged until 1995 when it was revised again. The MORECS which was in place between 1981 and 1995 is called version 1.0, while the 1995 revision produced version 2.0. A few customers continued with ESMD until 1995 when it ceased.

Since 1981 there have been considerable changes in the agricultural industry together with the availability of new soils databases. The cropping patterns in MORECS 1.0 refer to the situation in the 1960s, but by the early 1990s the area of winter cereals had increased at the expense mainly of spring barley, the area of grassland had reduced in some areas and a new crop, oil-seed rape, had developed to become the third commonest crop in UK. At the same time the Common Agricultural Policy of the European Union had introduced the set-aside policy which asked for up to 15% of cereal land to be removed from cereals production. The availability of computer-accessible soils databases provided a way for MORECS to have access to real soil data for its calculations of soil moisture.

In this report the version of MORECS which produces output in a square format is discussed. However, a single-site version is also available (i.e. rainfall from a single rain gauge with the choice of on-site or nearby climate data).

This report is an update to Hydrological Memorandum 45 which describes MORECS 1.0. Much of the basic science remains unaltered, but other areas have been revised with a few completely new topics.

Comparison summary of MORECS 1.0 and 2.0

Factor	MORECS 1.0	MORECS 2.0
Land use	Typical of 1960s	Typical of 1990s including oil-seed rape, set-aside, forestry area from satellite data, revised urban areas.
Soils	High, medium, low available water is standard everywhere	Real soils data used to find range of AWC in each square. Scotland and N Ireland found by analogue with English squares.

Note: AWC is the available water capacity for the crop and soil combination.

2. The purpose of MORECS

MORECS has been designed to provide estimates of weekly and monthly evaporation and soil moisture deficit in the form of averages over 40 x 40 km grid squares over the United Kingdom, using daily synoptic weather data as its inputs. The outputs can assist a variety of users; for example in the assessment of catchment water balance, the leaching of nutrients and short-term irrigation requirements. A specific need is for the information to be available to the user as soon as possible after calculation.

3. Outline of MORECS

The system has five main components (Table 3.1)

Table 3.1. The components of MORECS

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

The first is the daily extraction from the Synoptic Data Bank at Bracknell of values of the meteorological variables which are sometimes called the Penman variables (sunshine, temperature, vapour pressure, wind speed), and rainfall. Objective interpolation is then used to obtain grid-square average values of each variable. The next step is the calculation of daily potential evapotranspiration (PE) for each grid square for a range of surface covers from bare soil to forest, using a modified form of the Penman–Monteith equation. In the third part of MORECS the PE estimates are converted to estimates of actual evaporation (AE), by progressively reducing the rate of water loss from the potential value to zero as the available soil moisture decreases from $p\%$ of its maximum value to zero. The value of p depends upon the soil-crop combination and ranges from 60% for bare soil to 25% or less for some crops and soils. In each square these calculations are done for the median AWC soil and for the 10 and 90 percentile AWC value. The next part calculates the daily water balance under the various types of cropped surfaces, and also under the average land use for each square, in this case using the relative proportions of the various surfaces in each square. The final stage is the production of maps and tables showing the grid-square weekly averages of the Penman variables, and also PE, AE, soil moisture deficit (SMD), stress (AE/PE) and effective precipitation (EP) (also sometimes called hydrologically effective rainfall (HER) or 'excess rain') for the various crops and real land use. The distribution of output is normally by facsimile, but it is also possible to receive data by electronic mail and by post.

4. Detailed description of the system

4.1 Data collection, averaging and interpolation

4.1.1 Data collection: the network of stations and form of data storage

The network of stations supplying synoptic data which are used by MORECS is shown in Fig. 1 (sunshine) and Fig. 2 (rainfall). Rainfall and sunshine are reported directly as daily totals. The other three variables are usually reported several times each day, though a few stations make observations only once daily, at 0900, when 24-hour maximum and minimum temperatures, and the 0900 vapour pressure are recorded. All these data are available at Bracknell almost immediately after 0900 and are stored in the main data bank (MIDAS) there.

4.1.2 Method of averaging data

Daily mean values of air temperature for each station are calculated by averaging observations at 03, 09, 12, 15 and 21 UTC. Where any of these observations are missing, the daily mean temperature is taken as the average of the daily maximum and minimum values. Vapour pressure shows relatively small diurnal variations on average (Barrie and Wylie, 1980) and is obtained either by averaging observations (at 03, 09, 15 and 21 UTC) when more than one of these is taken each day, or from the single 0900 value. The daily mean wind speed is calculated as the average of those taken at any observations at the hours 03, 09, 15 and 21 UTC: the station is used even when only a single observation is available in the 24-hour period. The calculation of daily averages is done each day and the results are stored for use in the interpolation routines described below.

No data-averaging is performed with Single Site MORECS. In this case the data are taken direct from a station. If any data are missing then values from nearby sites are used if possible.

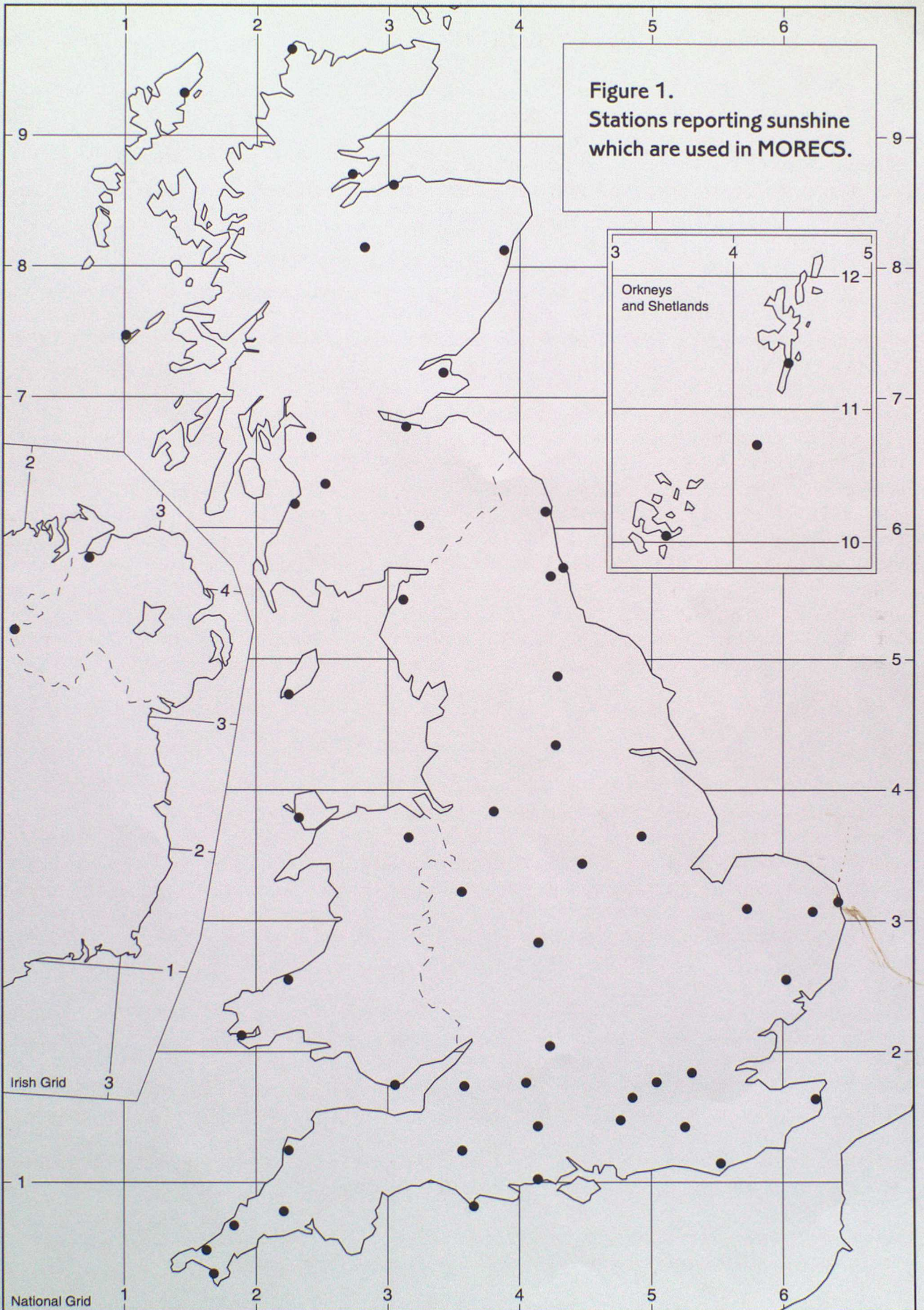

Figure 1.
Stations reporting sunshine which are used in MORECS.

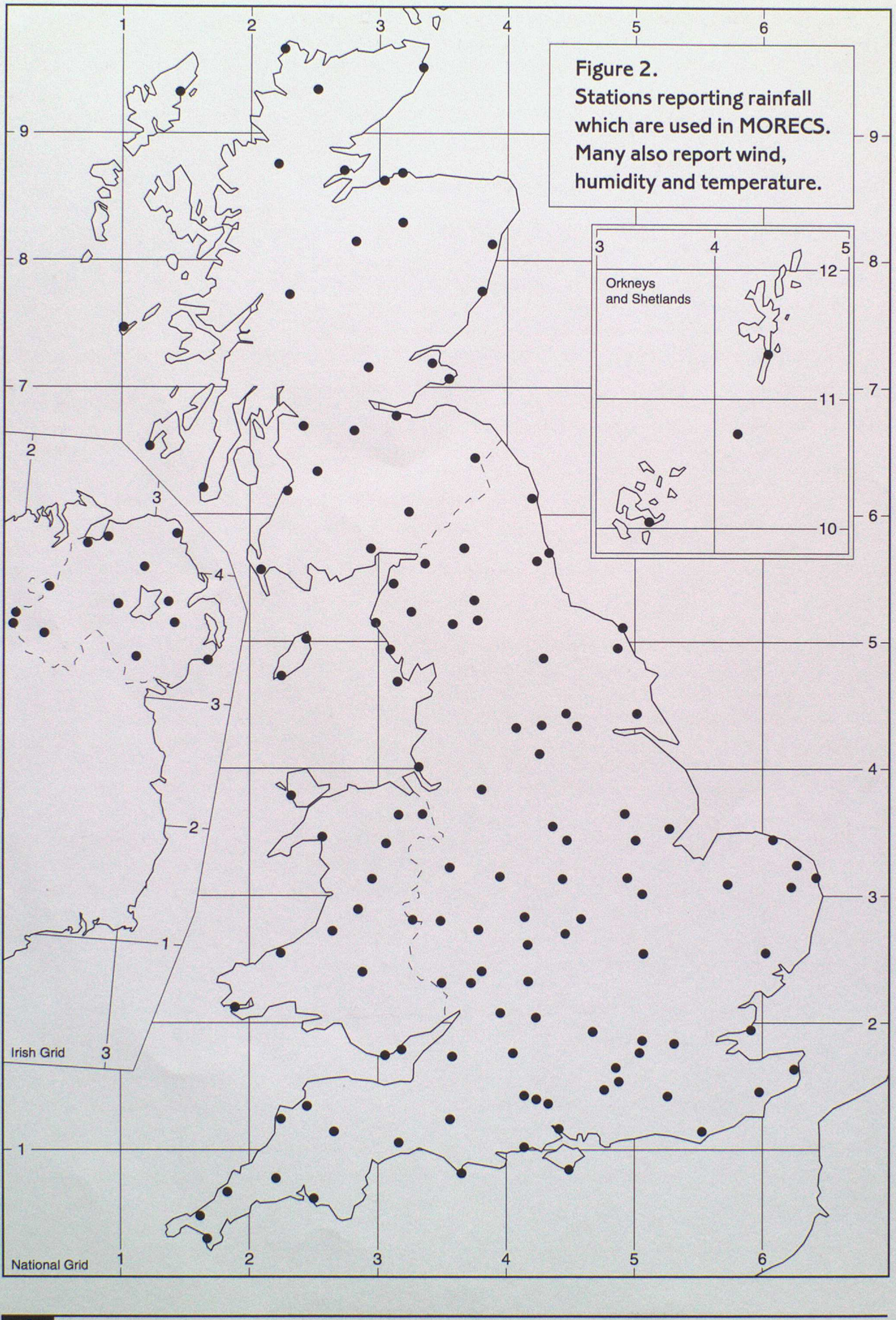

Figure 2.
Stations reporting rainfall which are used in MORECS. Many also report wind, humidity and temperature.

4.1.3 Interpolation of daily average station data to MORECS square estimates

The station data are first normalized or standardized as follows:

(i) Rainfall is expressed as a percentage of the annual station average.

(ii) Sunshine is converted to percentage of the average daily duration for the month.

(iii) Temperature and vapour pressure are 'reduced' to sea level, using lapse rates of, respectively, –0.6 °C/100 m and –0.025 mb/100 m (1 mb = 100 Pa).

(iv) The 10 m wind speed is converted to a value appropriate to a standard site using an empirical factor related to the general terrain roughness around the station.

Interpolation to obtain 40 x 40 km square values is now carried out. First the nine nearest stations to the centre of each square are selected, irrespective of whether they have data, up to a maximum of 100 km from the centre. However, if there is a station within 0.5 km of the centre then its observations are used alone. Otherwise, from the nine stations there are chosen the six nearest with data, but with the proviso that there are no more than two stations in each octant. If less than three stations are found then an inverse distance squared method of interpolation is used, otherwise plane-fitting is carried out (Shearman and Salter, 1975).

The grid-square values are then found. In the case of rainfall this involves the conversion of the percentage value to millimetres using average annual rainfall (1961–90) for the square. Similarly sunshine is expressed in hours by using the square-average mean daily duration for the month (1961–90). The interpolated temperatures and vapour pressure are adjusted to the mean altitude of each square. Finally the wind speed values are converted to squares estimates by applying a correction which takes into account the average terrain roughness for the square.

The errors involved in the use of these interpolation methods are unlikely to be large for temperature and humidity which usually show only slow changes with distance after conversion to sea level. Acceptable estimates of wind speed will also be obtained usually. Greater difficulties are experienced with sunshine. The network of sunshine recorders is fairly sparse, even when both synoptic and climatological stations are considered and so it is difficult to find representative long-term daily average values of sunshine duration for the month in each square. This is especially so where the square includes much high ground, because of the lack of upland measuring sites. For these reasons it is likely that square values of sunshine duration will be overestimated for squares with large amounts of high ground. At the time of writing the traditional Campbell–Stokes sunshine recorder is gradually losing favour to solar radiation recorders. It seems likely that the sunshine data in MORECS will be augmented by values of solar radiation in the future.

Rainfall shows large spatial variation, even over uniform terrain, especially in summer. It is possible to establish fairly reliable long-term average annual rainfall for each square using data from the several thousand rainfall stations. This means that in the very long term the estimates of MORECS square rainfall derived from the limited synoptic rainfall data will be satisfactory. In the shorter term though, such estimates can be misleading, and for this reason it is recommended that those who use MORECS outputs for irrigation scheduling should install their own rain gauge.

4.2 Data analysis to obtain evaporative demand over each grid square

4.2.1 Introduction

Central to MORECS is the scheme used to find the potential and actual evapotranspiration from the various surfaces which the system considers. Inadequate treatments here are likely to produce systematic errors in calculated evaporation. The corresponding percentage errors in soil moisture deficit will often be larger, since SMD is determined by differences between evaporation and rainfall, with the latter quantities having similar orders of magnitude for much of the year. It is possible to write down physically rigorous equations which will, in principle, provide very accurate estimates of evaporation. In practice the solution of the equations (to allow, for example, for the diurnal changes in atmospheric stability) is impossible analytically: the iterative methods which have to be used instead are too time-consuming for operational use. Simplification is therefore needed, with a consequent loss of accuracy. In fact the major errors in MORECS arise through shortcomings in the weather data (section 4.1.1), and in the correct specification of crop physiology. The errors involved in simplifying the treatment of the physical processes can be made negligible by comparison with the others.

MORECS uses a slightly modified version of the Penman–Monteith equation to calculate the potential and actual evapotranspiration, in the latter case adjusting the bulk surface (or canopy) resistance according to the size of the SMD. Calculations are done separately for the day- and night-time periods, with the 24-hour mean values of wind and temperature being adjusted empirically according to which period is being considered (Barrie and Wylie, 1980).

4.2.2 The basic calculation of evapotranspiration: the Penman–Monteith equation

The Penman–Monteith equation provides a physically based means of calculating water loss from any surface. The equation is

$$\lambda E = \frac{\Delta(R_n - G) + \rho C_p(e_s - e)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad (4.1)$$

where

E = rate of water loss (kg m^{-2} s^{-1})
Δ = rate of change of saturated vapour pressure with temperature (mb °C^{-1})
R_n = net radiation (W m^{-2})
G = soil heat flux (W m^{-2})
ρ = air density (kg m^{-3})
C_p = specific heat of air at constant pressure (1005 J kg^{-1})
e_s = saturation vapour pressure at screen temperature (mb)
e = screen vapour pressure (mb)
λ = latent heat of vaporization ($\cong$ 2465000 J kg^{-1})
γ = psychrometric constant (= 0.66 for temperatures in deg C and vapour pressure in millibars)
r_s = bulk surface (canopy) resistance (s m^{-1})
r_a = bulk aerodynamic resistance (s m^{-1})

Direct measurements of R_n are not available for use in MORECS and so R_n has to be estimated using empirical formulae (section 4.2.2.1). These formulae assume that the effective surface temperature is equal to screen temperature. This introduces errors, but an attempt to correct them may be made by modifying slightly the Penman–Monteith equation along the lines suggested by Monteith (1981) and Jones (1992). Thus one may write

$$R_n = R_{ne} + C \quad (4.2)$$

where

R_{ne} = R_n calculated assuming $T_o = T_{scr}$
T_o = bulk surface temperature
T_{scr} = screen temperature
C = correction term (4.3)
$= \epsilon\sigma((273.1 + T_{scr})^4 - (273.1 + T_o)^4)$
ϵ = emissivity of surface (= 0.95)
σ = Stefan's constant (5.67 x 10^{-8} W m^{-2} K^{-4})

For small values of $T_{scr} - T_o$, Eq (4.3) reduces to

$$C \cong 4\epsilon\sigma(273.1 + T_{scr})^3(T_{scr} - T_o)$$
$$= b(T_{scr} - T_o) \quad (4.4)$$

Thus,

$$R_n = R_{ne} + b(T_{scr} - T_o) \tag{4.5}$$

The new combination equation may now be derived. The energy balance at the surface is

$$\lambda E = R_{ne} - G - H - b(T_o - T_{scr}) \tag{4.6}$$

where
H = upward flux density of sensible heat from the surface (W m^{-2}).

The resistance equation for this flux density is

$$H = \rho C_p(T_o - T_{scr})/r_{ah} \tag{4.7}$$

where
r_{ah} = bulk resistance to transfer of sensible heat from its origin at the surface, up to screen height.

Similarly

$$E = \rho(q_o - q_{scr})/(r_s + r_{ae}) \tag{4.8}$$

where
q_o = specific humidity in the substomatal cavities of the surface cover ≅ saturation specific humidity at bulk surface temperature, q_s
r_s = bulk resistance to transfer of water vapour from within the sub-stomatal cavities to the (bulk) foliage surface
r_{ae} = bulk resistance to transfer of water vapour from bulk foliage surface up to screen height.

Also

$$\begin{aligned} q_o - q_{scr} &= q_o - q_s(T = T_{scr}) + q_s(T = T_{scr}) - q_{scr} \\ &\cong \Delta'(T_o - T_{scr}) + \delta q \end{aligned} \tag{4.9}$$

where
Δ' = rate of change of saturation specific humidity with temperature
δq = specific humidity deficit at screen height

Thus

$$E = \rho(\Delta'(T_o - T_{scr}) + \delta q)/(r_s + r_{ae}) \tag{4.10}$$

Now,

$$r_{ae} \cong r_{ah} = r_a$$

Then, from Eq (4.6) and (4.7)

$$\lambda E = R_{ne} - G - (T_o - T_{scr})(\rho C_p/r_a + b) \tag{4.11}$$

Eliminating $(T_o - T_{scr})$ between Eq (4.10) and (4.11)

$$E(1 + r_s/r_a) = \rho\delta q/r_a + \frac{\Delta'((R_{ne} - G) - \lambda E)}{C_p(1 + br_a/\rho C_p)}$$

or,

$$E(C_p(1 + r_s/r_a)(1 + br_a/\rho C_p) + \Delta'\lambda) = \rho C_p \delta q(1 + br_a/\rho C_p)/r_a + \Delta'(R_{ne} - G)$$

Thus,

$$\lambda E = \frac{\Delta'(R_{ne} - G) + \rho C_p \delta q(1 + br_a/\rho C_p)/r_a}{\Delta' + C_p(1 + r_s/r_a)(1 + br_a/\rho C_p)/\lambda} \qquad (4.12)$$

Writing this equation in terms of vapour pressure rather than specific humidity leads to

$$\lambda E = \frac{\Delta(R_{ne} - G) + \rho C_p(e_s - e)(1 + br_a/\rho C_p)/r_a}{\Delta + \gamma(1 + r_s/r_a)(1 + br_a/\rho C_p)} \qquad (4.13)$$

This is the combination equation used in MORECS.

4.2.2.1 Available energy: short- and long-wave radiation, the effects of cloud and soil heat flux

The downward daily total of short-wave radiation at the surface (R_c) is expressed in terms of the radiation flux density (R_a) at the top of the atmosphere using the scheme of Cowley (1978) which involves application of the empirical relation

$$R_c = R_a(\eta(a + bn/N) + c(1 - \eta)) \qquad (\text{W hr m}^{-2}) \qquad (4.14)$$

where

$$R_a = \int_{t_1}^{t_2} S \sin\Theta dt$$

$$= \int_{t_1}^{t_2} S(\sin\delta \sin\phi - \cos\delta \cos\phi \cos\frac{\pi t}{12})dt$$

$$= S((t_2 - t_1)\sin\delta \sin\phi + \frac{12\cos\delta \cos\phi(\sin\pi t_1/12 - \sin\pi t_2/12))}{\pi} \qquad (4.15)$$

Θ = solar elevation
δ = solar declination
= $0.41\cos(2\pi(d - 172)/365)$ (radians)
d = day of year ($1 \equiv 1$ January)
ϕ = latitude
S = solar constant
= $1360(1 + 0.035\cos(2\pi d/365))$ (W m^{-2}) (4.16)
(Hughes et al, 1977)
t_1 = local time of sunrise
= $\frac{12}{\pi}\arccos(\tan\delta \tan\phi + 0.0145/(\cos\delta \cos\phi))$ (4.17)

this expression allows for the refraction (~34′) and sun radius (~16′) so that sunrise occurs when the sun centre is still 50′ below the horizon.

t_2 = local time of sunset
= $24 - t_1$
N = day length
= $t_2 - t_1$
= $24 - t_1$
n = measured number of hours of bright sunshine
η = 0 if $n = 0$
η = 1 if $n = >0$

a and c are independent of season, with respective values of 0.24 and 0.15, varying geographically by about ±0.02. b varies both seasonally and geographically, increasing from about 0.5 in winter to 0.55 in summer, with a further geographic variation of around 0.05.
The net short-wave radiation at the surface is

$$R_{ns} = (1 - \alpha)R_c \tag{4.18}$$

where α is the albedo of the surface. Values of albedo used in MORECS for different surfaces are shown in Table 4.2.1.

Table 4.2.1. MORECS albedos

Surface type	**albedo**
Grass	0.25
Cereals	0.25
Potatoes	0.25
Oil-seed rape	0.25*
Sugar beet	0.25
Orchards	0.25
Deciduous trees	0.17
Upland**	0.25
Riparian	0.25
Conifers	0.12
Impervious Urban	0.10
Water	0.05
Bare soil (dry)	0.10, 0.20, 0.30 (a)
Bare soil (wet)	0.05, 0.10, 0.15 (a)

* This ignores the higher reflectivity during flowering.
** The upland class includes set-aside.
(a) Values refer respectively to soils of high (the 90-percentile AWC in a square), the median AWC in a square and low (the 10-percentile AWC in a square).

The values in Table 4.2.1 for the various types of vegetation refer to a fully developed crop cover. In the case of an incomplete cover a simple empirical correction to albedo is used:

$$\left.\begin{aligned}\alpha &= \alpha_s + 0.25(\alpha_c - \alpha_s)L \qquad && L \leq 4 \\ &= \alpha_c && L > 4\end{aligned}\right\} \tag{4.19}$$

where
α_s = albedo for bare soil
α_c = albedo for full crop cover
L = leaf area index

The incoming long-wave radiation ($R_{L\downarrow}$ is estimated using the technique of Brutsaert (1975). Unlike most other methods, Brutsaert's has a minimum of empiricism, being based on the equations of radiative transfer. The expression for clear skies is

$$R_{L\downarrow} = a'\sigma K_{scr}^4 (e_{scr}/K_{scr})^{1/7} \qquad (\mathrm{W\ m^{-2}}) \tag{4.20}$$

where
e_{scr} = vapour pressure at screen height
K_{scr} = screen temperature (K)

The value of a' is slightly dependent on assumptions about the variations of temperature and vapour pressure with height in the lowest few kilometres of the atmosphere. Brutsaert's treatment suggested a value about 1.24, but a comparison with experimental data gives a value of around 1.28, which is used in MORECS (Barrie, 1981).

Upward long-wave radiation from the surface is (putting $K_{scr} \cong K_{surface}$)

$$R_{L\uparrow} = \epsilon\sigma K_{scr}^4 \qquad (\mathrm{W\ m^{-2}}) \tag{4.21}$$

where the emissivity ϵ is assumed to be 0.95. The net long-wave radiation for clear skies is then

$$R_{LN} = \epsilon\sigma K_{scr}^4 (1.28(e_{scr}/K_{scr})^{1/7} - 1) \qquad (\mathrm{W\ m^{-2}}) \tag{4.22}$$

The effects of cloud on R_{LN} are assumed to be those suggested by Linacre (1968) so that the general expression is

$$R_{LN} = \epsilon\sigma K_{scr}^4 (1.28(e_{scr}/K_{scr})^{1/7} - 1)(0.2 + 0.8n'/N) \qquad (\mathrm{W\ m^{-2}}) \tag{4.23}$$

For daytime calculations n' takes a value equal to the number of hours of bright sunshine. At night the amount of cloud is usually smaller than during the day (Barrie, 1980), by about 10% typically, so that $n' \cong 1.1n$ (with a maximum value of n/N limited to 1.0).

Following Monteith (1958) the daytime flux density of heat into bare soil is assumed to be

$$G_d = 0.3R_{Nd} \tag{4.24}$$

where R_{Nd} is the average daytime net all-wave radiation flux density, given by

$$R_{Nd} = R_{LN} + (1 - \alpha)R_c/(t_2 - t_1) \tag{4.25}$$

The corresponding value for a grass-covered surface is

$$G_d = 0.2R_{Nd} \quad (4.26)$$

and for other crops is

$$G_d = (0.3 - 0.03L)R_{Nd} \quad (4.27)$$

The night-time value for soil heat flux is calculated using a scheme suggested by Wales-Smith and Arnott (1980). They used measurements of soil temperature at Kew with estimated soil thermal capacities to calculate the average monthly heat storage in the soil, and the corresponding average flux density of heat at the soil surface. Values of daily heat storage found in this way are shown in Table 4.2.2:

Table 4.2.2. Average daily heat storage in the soil (*P*)

J	F	M	A	M	J	J	A	S	O	N	D	
–137	–75	30	167	236	252	213	69	–85	–206	–256	–206	(A)
–5.7	–3.1	1.3	7.0	9.8	10.5	8.9	2.9	–3.5	–8.6	–10.7	–8.6	(B)

(A) Values in W hr m^{-2}.
(B) Values in W m^{-2} meaned over a day.

These values are assumed to apply over the whole MORECS grid. The average night-time value of G is

$$G_n = \frac{P - (t_2 - t_1)G_d}{2t_1} \qquad (\text{W m}^{-2}) \quad (4.28)$$

Finally, the available energy is calculated from

$$\left.\begin{aligned} &\text{daytime available energy} = R_{nd} - G_d \\ &\text{night-time available energy} = R_{LNn} - G_n \end{aligned}\right\} \quad (4.29)$$

where R_{LNn} is from Eq 4.23 at night.

4.2.2.2 Aerodynamic resistance

The aerodynamic resistances for heat and water vapour transfer are defined by Eq (4.7) and (4.8). Experimental evidence shows that they are negligibly different in size. The resistances may also be defined in terms of the vertical eddy diffusion coefficient for heat and water-vapour transfer ($K_{H,E}(z)$), thus demonstrating the role of atmospheric turbulence in transferring heat and water vapour away from the surface. In this form the definition is

$$r_{aH} = r_{aV} = r_a = \int_{z_{T,q}}^{z-d} (1/K_{H,E}(z))\,dz \quad (4.30)$$

Here $z_{T,q}$ is the roughness length of the surface for heat and water vapour transfer. Momentum may be transferred to surfaces by pressure forces as well as molecular diffusion and so the roughness length for momentum transfer (z_o) is larger than $z_{T,q}$. Thom (1975) developed this idea and showed that

$$z_{T,q} \cong 0.2z_o \quad (4.31)$$

Typical values for z_o are about $0.1h$, where h is the crop height, and so $z_{T,q} \cong 0.02h$.

In Eq (4.30) the upper limit of integration is $z - d$, rather than z. This acknowledges that the effective mean height at which the heat and water vapour originates is $d + z_{T,q}$, where d is the zero-plane displacement height: it has a typical value of about 0.6h (Monteith and Unsworth, 1990). The temperatures and humidities which MORECS uses are measured over short grass at screen height (1.2 m), for which d can be ignored. The assumption is made that these data will also apply at a height of 1.2 m above the zero-plane of any other surface. Hence the MORECS r_a should be defined by

$$r_a = \int_{z_{T,q}}^{z'-d} (1/K_{H,E}(z))\,dz \qquad (4.32)$$

where

$$z' = 1.2 + d \quad \text{(m)}$$

In conditions of near-neutral atmospheric stability the variations of wind and temperature with height are logarithmic, and Eq (4.32) may be integrated to give (Thom and Oliver, 1977)

$$r_a = (1/k^2 U(z'))\ln(1.2/z_o)\ln(1.2/z_{T,q}) \qquad (4.33)$$

MORECS assumes that its measured 10 m winds ($U_m(10)$) are equal to the wind speed $U(10 + d)$ at $(10 + d)$ m above the surface underlying the crop, or that wind speeds at 10 m above the zero-plane are the same for different crops. This is a bad approximation over very tall, very rough crop covers (e.g. conifers) and for these cases, following Oliver (1974), the relation

$$\left.\begin{aligned} U(10 + d) &= 0.6U_m(10) \\ &= 0.7U_m(10) \quad \text{(for orchards)} \end{aligned}\right\} \qquad (4.34)$$

is used for trees in full leaf, in a somewhat different treatment outlined at the end of this section. From the logarithmic wind profile it may be shown that

$$U(z')/U(10 + d) = \ln(1.2/z_o)/\ln(10/z_o) \qquad (4.35)$$

Using the relation $z_o = 0.1h$, and Eq (4.33) and (4.35) and, where appropriate, (4.34), one may then calculate r_a, noting that Eq (4.33) and (4.35) give

$$r_a = (6.25/U(10 + d))\ln(10/z_o)\ln(6/z_o) \qquad (4.36)$$

The treatments described by the above equations are poor approximations over very rough surfaces where the level $(1.2 + d)$ m may be well within, rather than above the foliage. In these cases the upper reference level is taken to be $(10 + d)$ m above the ground surface, and the vapour pressure deficit calculated from the screen data is assumed to apply at this height over the forested area. r_a is then given by

$$r_a = (6.25/U(10 + d))\ln(10/z_o)\ln(50/z_o) \qquad (4.37)$$

Then, for mature conifers and deciduous trees in full leaf, for which $z_o \cong 1m$

$$\begin{aligned} r_a &= 56.3/U(10 + d) \\ &\cong 94/U_m(10) \end{aligned} \qquad (4.38)$$

Use of the neutral forms for r_a (Eq (4.36), (4.38)) requires some justification. Thompson (1981) made exact calculations of evapotranspiration using the Penman–Monteith equation with given input values for available energy, vapour pressure deficit, wind speed, surface roughness, temperature and surface resistance, with full allowance for non-neutral stability in calculating r_a, and with and without correction to available energy resulting from surface heating. The results were compared with estimates made using the method outlined above, and with estimates obtained using the modified form of Penman's original form for r_a suggested by Thom and Oliver, also with and without allowance for the effects of surface heating on available energy. The method described in detail above gave the best agreement with the exact calculations, and for typical values of the input variables was usually within better than 10% of the exact model. It showed a small overall bias towards underestimation, but this conveniently compensates to some extent for neglect of the available energy used in photosynthesis by the transpiring crop.

4.2.2.3 Bulk surface (canopy) resistance when soil moisture is not limiting

Correct specification of the surface resistance is crucial to the satisfactory running of MORECS. Surface resistance (r_s) varies with type and age of crop, and with external factors such as light intensity. The aim has to be to incorporate a simple, but realistic scheme which will account for the seasonal changes including variable leaf area index for the main surface types. For most of these surfaces it is necessary to calculate r_s on a daily basis for day and night-time using, where appropriate, the crop phenology data in Annexe A.

For seasonal crops the surface will change from bare soil to densely foliated. Water may be extracted directly from both the soil and the crop, and the surface resistance has to be calculated taking both these processes into account. The basic scheme follows that of Grant (1975) and uses the expression

$$1/r_s = (1 - A)/r_{sc} + A)/r_{ss} \qquad (4.40)$$

where

r_{sc} = surface resistance of the crop, freely supplied with water, and dense enough for evaporation from the soil to make a negligible contribution

r_{ss} = surface resistance of bare soil (assumed to be 100 s m^{-1} for wet soil)

$A = f^L$

For bare soil van de Griend and Owe (1994) measured r_{ss} during the dry-down from the field capacity state. During the first stages of drying the soil surface was wet and the resistance was between almost zero and a few tens of s m^{-1}. However, when the top-most layer had dried r_{ss} increased to several hundred s m^{-1}, but fell to low values at night when the moisture profile recovered by capillary activity. When about 40% of the available water was evaporated then a deep, dry layer had formed and the resistance was high most of the time. The value of 100 s m^{-1} is approximately the mean value during the time of maximum evaporation from the bare soil.

Grant found that f for barley was about 0.7, and this value is assumed to apply to all the crops treated by MORECS. Eq (4.40) was derived for daytime conditions and assumes that the parallel contributions of soil and crop resistance to their combined resistance are roughly proportional to the amount of incident radiation which each of them absorbs. At night the leaf stomata are closed and the crop resistance r_{sc} is assumed to be the sum of the individual leaf (cuticular) resistances in parallel. These in turn are taken to be directly in parallel with the soil resistance so that

$$1/r_s = 2L/r_{sc(night)} + 1/r_{ss} \qquad (4.41)$$

A typical leaf resistance when stomata are closed is several thousand s m^{-1}: the form of Eq (4.41) used by MORECS is

$$1/r_s = L/2500 + 1/r_{ss} \qquad (4.42)$$

It is not possible to justify the last equation convincingly since it ignores the effects of turbulent resistances in the crop canopy. However, evaporation is usually small at night so errors introduced by Eq (4.42) will also be small. Values for r_{sc} which are used by MORECS during the daytime are given in Table 4.2.3.

Table 4.2.3. Daytime values of surface resistance (r_{sc}) for dense, green crops freely supplied with water

Type of crop	r_{sc} (s m^{-1})
Grass, riparian land	80 (J, F), 60 (M), 50 (A), 40 (M), 60 (J, Jy) 70 (A, S, O), 80 (N, D)
Cereals	40
Potatoes, sugar beet	40
Oil-seed rape	40
Deciduous trees	80
Conifers	70 (a)
Upland (b)	160 (O, N, D, J, F, M, A), 70 (M, J, Jy, A, S)
Orchards	See text
Reference crop (c)	40
Bare soil	100
Water	0

(a) At zero vapour pressure deficit and 20 °C: assumed independent of r_{ss}, i.e. $r_s = r_{sc}$ since $A \cong 0$.
(b) Assumed independent of leaf area of the ground cover, i.e. $r_s = r_{sc}$.
(c) Reference crop is an idealized green crop which has constant properties throughout the year, including the r_{sc} value.

The value of 40 s m^{-1} is used for most crops and is chosen between the values of 30 s m^{-1} for irrigated crops (Choudhury and Idso, 1985) and 50 s m^{-1} for 'well-watered' crops mentioned by Jamieson, Francis, Wilson and Martin (1995).

4.3 Crop modelling

4.3.1 Introduction

The crop models which are used in MORECS are idealized representations of crop growth which describe the main features which MORECS needs. The models describe aspects such as development (progress through the growth stages), leaf area index (to determine transpiration), crop height (for the aerodynamic resistance r_a), the variation of r_{sc} with weather (for conifers) and crop age (cereals and oil-seed rape), and the changes in the available water capacity as roots grow in annual crops. The crops are considered in turn with the main points described.

4.3.2 Models for the different crops

Grass

A permanent pasture is assumed with the leaf area index varying month by month as in Table 4.3.2. The height is assumed to be 0.15 m throughout the year. This is clearly a compromise between a well-grazed sward which would be shorter and less leafy, and crops grown for hay or silage which would make more growth before being cut. The canopy resistance values reflect the effects of seasonal changes in temperature and light intensity and of leaf age (Table 4.2.3). Roots are assumed to be active throughout the year with old ones being replaced by young roots so that the available water capacity remains constant.

Winter wheat and winter barley

These two crops along with oil-seed rape form the bulk of the autumn sown crops throughout the UK. A good standard of husbandry is assumed with application of the recommended rates of fertilizer and good control of diseases and pests. Crop development is by calendar date with fixed dates of sowing, emergence, maximum leaf area and harvest in each square (Annexe A). The emergence date is 15 October in all squares and is really a crop-establishment date rather than true emergence which is usually earlier. A period of autumn growth is assumed from emergence to 1 December after which growth is assumed to be static until a date in early spring from which growth begins again. The leaf area index is as follows

Winter wheat

$$
\begin{aligned}
&L = 0.25 && \text{(emergence to 1 December)} \\
&L = 0.50 && \text{(1 December to date of spring start)} \\
&L = 0.5 + (L_{max} - 0.5)(d - d_e)/(d_f - d_e) \ \ldots\ldots && d_e<d<d_f \\
&L = L_{max} && d_f<d<d_h
\end{aligned}
\qquad (4.43)
$$

Winter barley

$$
\begin{aligned}
&L = 0.5 && \text{(emergence to 1 December)} \\
&L = 0.9 && \text{(1 December to date of spring start)} \\
&L = 0.9 + (L_{max} - 0.9)(d - d_e)/(d_f - d_e) \ \ldots\ldots && d_e<d<d_f \\
&L = L_{max} && d_f<d<d_h
\end{aligned}
\qquad (4.44)
$$

Where d_e, d_f, d_h refer to the dates of spring start, full leaf cover and harvest. L_{max} is the maximum leaf area index given in Table 4.3.2.

From emergence to the date of the spring start to growth the crop height h is assumed to be 0.08 m. The subsequent variation is according to

$$
\left.
\begin{aligned}
&h = h_1 + (h_2 - h_1)[d - d_e)/(d_f - d_e)]^2 \ \ldots\ldots && d_e<d<d_f \\
&h = h_2 && d_f<d<d_h
\end{aligned}
\right\}
\qquad (4.45)
$$

Where h_1 is 0.08 m and the final height h_2 is 0.8 m.

For well-watered crops the effects of crop age on the bulk canopy resistance are included by writing

$$
r_{sc} = r_{sc}(\text{min}) + 50\left(\frac{d - d_f}{d_h - d_f}\right) + 500\left(\frac{d - d_f}{d_h - d_f}\right)^3 \qquad (4.46)
$$

so that r_{sc} is large (about 600 s m^{-1}) at harvest.

The crop available water is assumed to increase linearly from the bare soil value at emergence to twice this value by the end of autumn growth on 1 December. It then stays the same through the winter until the date of start of spring growth after which it increases linearly to the date of maximum leaf cover. It then stays constant until harvest.

Oil-seed rape

This crop is introduced for the first time in MORECS 2 and the opportunity has been taken of using a different modelling approach. Crop development and the leaf area are described in terms of thermal time (temperature sums above a base temperature of 4 °C), rather than by date. MORECS assumes that the sowing date is 1 September in all squares, but the subsequent growth depends mainly on temperature. The following references were used to construct the model: Mendham and Scott (1975), Evans and Ludeke (1987), Mendham, Shipway and Scott (1981), Evans (1981), Jenkins and Leitch (1986), Leach, Milford, Mullen, Scott and Stevenson (1989), Mendham, Russell and Jarosz (1990).

The thermal time starts to increase beginning on the day after sowing and is calculated as $\Sigma(\bar{T} - 4)$ where $\bar{T}$ is the daily mean temperature. When 80 degree days are reached the crop is assumed to have emerged and subsequent leaf growth is slow so that the leaf area index has increased to 0.1 after a further 240 day degrees. Thereafter the leaf area index increases at a rate of 0.014455 LAI/day degree (base 4). During the winter, from 15 November to 1 March, the short days slow down development and the day degrees are assumed to be only 0.43 as effective as outside this period. The plants are assumed to change from a vegetative to a reproductive state at 607 day degrees from sowing and the peak leaf area index is reached between 900 and 960 day degrees from sowing. However, if the value of 607 is reached before 15 November vernalisation is not assumed to be complete until that date and the difference between the thermal time and 607 is found and added on to all subsequent development stages. After the peak leaf area has been reached the leaf area index is assumed to decrease at a rate of 0.0133 LAI/day degree until it falls to 4.5 (the mass of pods) after which it stays constant. After 1310 day degrees from sowing the bulk stomatal resistance rises according to Eq (4.46), and harvest is assumed to be at 1660 day degrees.

Crop height is not allowed to exceed 0.15 m before 607 day degrees, but is allowed to increase to 1 m by the time of full leaf cover with height increments proportional to thermal time. The available water capacity increases with thermal time from the bare soil value at emergence to the maximum value at 900 day degrees from sowing and then stays fixed until harvest.

Spring barley

The development from emergence to maximum leaf cover and harvest is by calendar date. The leaf area is given by

$$L = (L_{max} - 0.1)(d - d_e)/(d_f - d_e) + 0.1 \quad \ldots\ldots\ldots\ldots \quad d_e < d < d_f \qquad (4.47)$$

where the leaf area index is 0.1 at emergence and remains at L_{max} until harvest. The effects of senescence on the bulk canopy resistance are represented by Eq (4.46). The available water is assumed to be equal to that for bare soil at emergence and increases linearly to the maximum value when full leaf cover is reached. The height is assumed to be 0.05 m at emergence increasing according to Eq (4.45) to a maximum value of 0.8 m.

Potatoes and sugar beet

The root crops are planted/sown in spring and harvested in autumn. Leaf area development for the root crops is given according to Eq (4.47) with a constant value after the date of full leaf cover. The bulk canopy resistance without water stress is set to a constant value throughout the season. For potatoes and sugar beet the available water increases linearly from that for bare soil at emergence to the maximum value when full leaf cover is reached. Both crops are assumed to be 0.05 m high at emergence with sugar beet reaching a maximum height of 0.35 m and potatoes 0.60 m.

Deciduous trees

The development of deciduous trees is described in terms of fixed dates for each square. From a date of bud burst it is assumed that 40 days elapse before full leaf cover (LAI = 6) has been attained, and similarly in autumn leaves are assumed to take 40 days to fall off after the leaf fall start date. During the winter a bare soil situation is assumed. The foliation state has a marked effect on the wind profile which is represented by means of an 'effective' height. The effective height is assumed to be 2 m at bud burst and increases linearly to 10 m at full leaf cover. The bulk stomatal resistance with no water stress is equal to 80 s m^{-1} with leaves present, increasing to 180 s m^{-1} at the end of the leaf fall phase, but takes the value 100 s m^{-1} during winter with no leaves. The available water capacity remains constant throughout the year.

Coniferous trees

The conifers are assumed to have a constant LAI = 6 throughout the year, a constant available water capacity and a fixed effective height of 10 m. A temperature dependence for r_{sc} is represented by

$$\left.\begin{aligned} r_{sc} &= 25r_{sc}(\min)/(T_{scr}+5) \;\ldots\ldots\ldots\; -5<T_{scr}<20 \\ &= r_{sc}(\min) \;\ldots\ldots\ldots\; T_{scr}>20 \\ &= 10^4 \;\ldots\ldots\ldots\; T_{scr}<-5 \end{aligned}\right\} \qquad (4.48)$$

where $r_{sc}(\min)(\delta e = 0)$ is found from Table 4.2.3 and the response to vapour pressure deficit δe (based on Grace et al., (1975)) is given by

$$r_{sc} = r_{sc}(\delta e = 0)/(1 - 0.05\delta e^{(1-\delta e^2)0.0001333}) \qquad (4.49)$$

where $r_{sc}(\delta e = 0)$ is found from Eq (4.48).

Orchards

Orchards are assumed to go through the deciduous tree cycle of bud burst, full leaf cover, leaf fall and a winter bare state according to a series of dates which are fixed for each square. Orchards are assumed to be largely grass-covered so that in winter with bare trees a grass model is used, and in the rest of the year the grass properties of leaf area and bulk canopy resistance are combined with those for trees. Table 4.3.1 shows some details.

Table 4.3.1. Properties of orchards during the growth cycle

	Bare	Bud burst to full cover	Full cover	Full to bare
Height (m)	*	3	3	2
Grass LAI	*	2.5	2.5	2.5
Tree LAI	0	0–2.5	2.5	2.5–0
Tree resistance	—	80	60#	80–180#
Grass resistance	*	50**		

* The value is as for grass.
** Grass and bare soil combined.
\# Trees and grass combined.

Upland and set-aside

The upland land class represents much of the unimproved grassland which is typical of upland areas. Other vegetation types such as heather etc. may also be present and there may be bare areas as well, but rooting depth is usually restricted by shallow soils or the presence of waterlogging. The growing season is typically short, while in winter growth is slow and there is usually much dead material present. The available water capacity is assumed to be half that for grass and the proportion which is freely available is taken to be the same as for grass. The canopy resistance value is assumed to be 70 s m^{-1} during the main growth phase from May to September (Lockwood, Jones and Smith (1989)), but increases to 160 s m^{-1} from October to April (Table 4.2.3).

As a result of the farm policies of the European Union arable farmers are required to take a portion of their land which grows cereals and oil-seed rape and revert it to a land use known as rotational set-aside. In addition there is also an option for set-aside outwith the rotational scheme. At present the rotational set-aside is 12% (10% for 1996–97) of the (cereals + oil-seed rape area). In MORECS 15% of the (cereals + rape area) is used so as to allow for the non-rotational set-aside. There are various options that can be chosen for set-aside land: it can be left to grow weeds, it can be sown with grass, it can be used to grow an 'industrial' crop. The common choice has been natural regeneration or grass. MORECS assumes a partial cover of weeds, including much grass, but there is no land preparation or fertiliser application and so the upland class has been used to represent this land use.

Water surfaces

Evaporation from water is estimated using Eq (4.13) and assuming a value of r_s of zero. In effect the water is treated as a kind of soil with no allowance for heat storage as would occur with large and deep water bodies. Because of this the MORECS estimates of water evaporation should only be used for water less than about 20 cm deep. For deep water the evaporation is likely to be overestimated in spring (as the water takes up heat) and underestimated in autumn (as the water gives up heat).

Riparian

Some of the land around water features such as lakes and rivers is assumed to have a permanent water table at shallow depth so that the vegetation (grass) has access to water at all times. The evaporation is assumed to be at the potential rate and the SMD is taken as zero always, however, an EP value is calculated.

Bare rock

Small areas of mountainous country are classified as rock and it is assumed that all water goes to run-off so that PE is ignored (with AE = 0) and with EP = rainfall.

Urban

Potential evaporation is calculated by assuming that the albedo is 0.1, the effective height is 15 m and the 'canopy' resistance is zero. However, the AE is limited to a maximum value of 0.5 mm which is assumed to be the 'AWC' of this land use. If the rainfall on a day is zero then AE is zero. If the rainfall is between zero and 0.5 mm then AE = rainfall.

Table 4.3.2. Maximum values of leaf area index

Crop	Green leaf area index
Grass, riparian	2.0 (Jan), 2.0, 3.0, 4.0, 5.0, 5.0 (Jun) 5.0, 5.0, 4.0, 3.0, 2.5, 2.0 (Dec)
Cereals	5.0
Potatoes	4.0
Sugar beet	4.0
Bare soil, rock, water and urban	0
Deciduous trees	6.0
Reference crop	5.0
Conifers	6.0
Orchards	see Table 4.3.1
Upland	3.5

No value is given for oil-seed rape because the value is calculated for each year, however, it is typically about 7.0.

Reference crop

This is a fictitious crop which has constant properties throughout the year. These are a minimum canopy resistance of 40 s m^{-1}, height 30 cm, a LAI of 5.0 and an AWC equal to cereals. It is intended to represent a leafy crop not represented by the others named above, but provided the actual crop has details which are similar to the reference crop.

A summary of the various crop heights is given in Table 4.3.3.

Table 4.3.3. Effective crop heights used in MORECS

Crop	Height (m)
Grass	0.15
Winter wheat[b]	0.08–0.80
Oil-seed rape[a]	0–1.0
Sugar beet[a]	0.05–0.35
Orchards[d]	0.15–3.0–2.0
Upland	0.15
Rock	15.0
Bare soil	0.05
Spring barley[a]	0.05–0.80
Winter barley[b]	0.08–0.80
Potatoes[a]	0.05–0.60
Deciduous trees[c]	2.0–10.0
Conifers	10.0
Urban	15.0
Water	0.005
Reference crop	0.30

(a) The range of values is from emergence to full leaf cover/harvest.
(b) The first value is an average from emergence to the date of the start of spring growth; the second is at full leaf cover/harvest.
(c) The range of values is for budburst to full leaf cover.
(d) The range of values is from the winter state (bare trees), next budburst and full cover and finally leaf fall.

4.4 Calculation of actual evaporation using a soil moisture extraction model

4.4.1 Extraction of water from soils and the derivation of AWC for soil/crop combinations

A fundamental and important soil property is the amount of water which can be supplied to plants which are growing in it. A large reserve of available water allows plant growth to continue during dry periods when the atmospheric demand (PE) exceeds rainfall. The soil water is held against gravity by capillary forces between the soil particles. If the soil particles are very small (such as a clay) then the capillary force, which is inversely proportional to the radii of the soil particles, is strong and plants have to exert considerable suction to extract all of the water. Conversely, a coarse, sandy soil retains most of the water under relatively low suction so that plants can easily extract most of the water. The AWC is obtained from a consideration of the suctions at which the water is held in the soil and the rooting pattern of the crop.

The method used in MORECS is that described by Thomasson (1995). In this method each crop is described by a characteristic pattern of rooting with depth together with an associated proportion of the soil water which is freely available (suction range 5–200 kPa (0.05–2.0 bar)), and that which is held under higher suction (suction range 200–1500 kPa (2.0–15.0 bar)). Table 4.4.1 gives details for some of the crops used in MORECS.

Table 4.4.1. Adjustment to AWC for particular crops

Crop	Depth (cm)	Suction (bar (kPa))
Wheat, barley	0–50	0.05–15.0 (5–1500)
Oil-seed rape	50–120	0.05–2.0 (5–200)
Potatoes	0–70	0.05–15.0 (5–1500)
Sugar beet	0–80	0.05–15.0 (5–1500)
	80–140	0.05–2.0 (5–200)
Grass	0–70	0.05–15.0 (5–1500)
	70–100	0.05–2.0 (5–200)

The table shows that for all crops except potatoes there is a densely rooted upper soil layer where all the water from field capacity (5 kPa) to the permanent wilting point (1500 kPa) is available to the crop. Beneath this there is a layer with sparser rooting where only the easily available water is available to the plants. In the case of potatoes the rooting pattern permits all the water within the root range to be available.

For each crop and soil combination the proportion of the easily available water to that held at higher suction can be found. The values range from about 50 to 79% (Table 4.4.2). A value of 65% is quoted in Jamieson et al. (1995) for the proportion which is freely available for soil which is densely occupied by roots. However, they conclude that a lower figure is more appropriate early in the life of a crop because the rooting is not so dense, but no account is taken of this because deficits are usually small then. In MORECS 1.0 the proportion of water freely available was held constant at 40% for all crops and all soils so that this represents a major change in the way that MORECS works.

The figures as in Table 4.4.1 are not available for all the types of vegetation which are represented in MORECS. For the other crops the following assumptions (based upon data from the literature and in the case of bare soil from data supplied by R Jones (personal communication, 1994)) are made in deriving the AWC:

(1) Upland AWC = 0.5 (grass AWC)
(2) Deciduous trees AWC = 2.3 (grass AWC)
(3) Conifers AWC = 1.9 (grass AWC)
(4) Bare soil AWC = 0.27 (grass AWC)

In the case of the trees the easily available proportion is taken to be similar to the cereals, while upland is assumed to be the same as for grass. For bare soil the first 40% of available water is assumed to be easily available.

4.4.2 Soils database and derivation of soils data for each square

The soils database called LANDIS (RJA Jones, personal communication, 1995) was used to derive soils data for each square. This database comprises information on the AWC of soils, among others, at a resolution of 1 km for England and Wales. For each crop the range of AWC in each of the MORECS squares was found and the median, the ten percentile and ninety percentile values were extracted. These values of AWC (and their corresponding proportions of freely available water) replace the MORECS 1.0 'medium', 'low' and 'high' AWC.

In Scotland and Northern Ireland an analogue approach was used and a square was chosen from England which most closely matched the geology and soils/climate of the square. In Annexe D is a list of the typical

AWC for grass in all squares. Table 4.4.2 shows the means of AWC and the freely available percentage, *P*, averaged over all the squares.

4.4.3 Relationship between surface resistance and soil moisture deficit

The basis of MORECS' soil moisture extraction model is the assumption that, for a dense crop intercepting all the incident solar radiation, the surface resistance remains constant while the easily available fraction (*P*%) is extracted. Thereafter the resistance increases progressively to very large values when all the available water is exhausted. This is broadly consistent with experimental results for crops subjected to moderate evaporative demand (e.g. Russell, 1980). A similar assumption is made for evaporation from bare soil, again in moderate agreement with experiment (Saxton et al., 1974, van de Griend and Owe, 1994).

Table 4.4.2. The median, 10-percentile and 90-percentile AWC and the per cent freely available (*P*) for various crops expressed as an average over all the MORECS squares

Crop		**AWC (mm)**	
	median	**10% ile**	**90% ile**
Grass	133 (62)	114 (57)	187 (70)
Winter wheat	134 (71)	114 (66)	192 (79)
Winter and spring barley	134 (71)	114 (66)	192 (79)
Oil-seed rape	134 (71)	114 (66)	192 (79)
Sugar beet	160 (71)	129 (66)	235 (79)
Potatoes	113 (53)	99 (50)	154 (60)
Orchards	161 (71)	136 (66)	230 (79)
Deciduous trees	305 (71)	262 (66)	429 (79)
Conifers	252 (71)	216 (66)	354 (79)
Upland	67 (62)	57 (57)	94 (70)
Bare soil	36 (40)	31 (40)	50 (40)

Typical crops do not intercept all incident radiation, especially during early growth, and so the contribution to evaporation from the underlying soil, must also be considered. This is done by relating r_{ss} to the soil moisture deficit and then combining it with a correspondingly corrected r_{sc}, using the relations discussed in section 4.2.2.3.

MORECS uses the simplifying assumption that the available water is held in two reservoirs X and Y, which at any time may contain reserves *x* and *y* mm. All water in X is freely available, while that in Y becomes increasingly difficult to extract as *y* decreases. Hence the total (maximum) available water ($x_{max} + y_{max}$) is distributed *P*% in X and (100 – *P*)% in Y. Water is drawn from the soil until X is completely exhausted, when extraction from Y begins. Rainfall is assumed to recharge X first of all, and only replenish Y when X is full. From earlier sections it was seen that the easily available water is distributed down the root profile and is not necessarily from the surface layer only.

Two cases are considered, one where *x* is non zero and the other when $x = 0$. In the first case the minimum canopy resistance values are used and the potential rate of evaporation will apply from the crop. However, the minimum value for bare soil (100 s m^{-1}) is only assigned to r_{ss} if the current value of ($x_{max} - x$) for the (soil + crop) combination is less than $x(\text{bare soil})_{max}$ (typically about 14 mm). Otherwise the assumption is made that

$r_{ss} = 100x(crop + soil)_{max} / (x(crop + soil) + 0.01x(crop + soil)_{max})$

r_s then follows from Eq (4.40).

In the second case $x = 0$ and $r_{ss} = 10^4$ s m^{-1}, and r_{sc} is increased according to the size of y by using:

$$r_{sc}(y) = r_{sc}(2.5/(1 - (y_{max} - y)/y_{max}) - 1.5)$$

where r_{sc} is taken from Table 4.2.3. When the surface is bare soil (without a crop) the surface resistance is calculated from

$$r_s = r_{ss} = 100 \text{ s m}^{-1} \qquad (x(baresoil)_{max} > x > 0)$$
$$= 100(2.5/(1 - (y(baresoil)_{max} - y)/y(baresoil)_{max}) - 1.5) \qquad (x = 0)$$

4.5 Calculation of water balance and effective precipitation

4.5.1 Treatment of intercepted water, including condensation

When the estimate of night-time evaporation is negative, r_s is set equal to zero and the calculation performed again in order to obtain an estimate of condensation. The treatment of interception is simplified by assuming that the effective daily rainfall is the sum of this condensation and rainfall.

A proportion (p) of the effective rainfall is intercepted by the crop overlying the soil, with a dense crop intercepting at a higher rate than a sparse one. The relation used is

$$p = 1 - 0.5^L$$

The interception is then pR where R is the rainfall. However, the maximum interception capacity per unit leaf area is assumed to be 0.2 mm so that the upper limit to interception is $0.2L$. In practice there may be more than one rainfall event each day, or some evaporation of intercepted water may occur while rain is still falling. In MORECS it is assumed that evaporation of intercepted water is slow in the winter months when the maximum daily interception is as above. In summer it is assumed that because of multiple rainfall events, the daily loss will be typically twice the value calculated by pR, but not greater than the rainfall. The multiplying factors used in each month are in Table 4.5.1.

Table 4.5.1. Factor enhancing simple interception to allow for multiple rainfall events, or for evaporation of intercepted water while rain is falling

Month	J	F	M	A	M	J	J	A	S	O	N	D
Factor	1.0	1.0	1.2	1.4	1.6	2.0	2.0	2.0	1.8	1.4	1.2	1.0

Each daytime or night-time calculation is performed with $r_{sc} = 0$ while intercepted water remains. Once the foliage is dry the rate of water loss is calculated for the remainder of the period using the r_{sc} value for dry leaves. Thus, total water loss from the surface is the sum: intercepted water + (rate of water loss (dry foliage))*number of hours while the foliage is dry. On those occasions when the evaporative demand is insufficient to evaporate all the intercepted water the amount remaining at the end of the day is not carried over but is assumed to fall to the soil.

4.5.2 Soil moisture deficit and effective precipitation

The information given in the previous sections explains how the daily evaporation is calculated. The difference between this evaporation and the rainfall, when added to the previous day's soil moisture deficit, gives the current soil moisture deficit. The rainfall is the total for 24 hours (0900–0900) and because of the procedure which is used to calculate SMD the assumption is therefore implicit that the rain falls at the start of the day and is then available to be evaporated during the day.

Typically in the summer the SMD will rise because rainfall is usually less than the evaporation. However, in late summer or autumn the evaporation falls and rainfall increases so that the SMD falls. There comes a point when the SMD has been reduced to zero (the state of 'field capacity'). Any further positive values of (rain – evaporation) are called effective precipitation (EP). There is no attempt to model or estimate 'run-off'.

In winter, when precipitation falls as snow and lies without melting, MORECS assumes that the EP is generated as usual. In such situations it should be borne in mind that the EP will only be realized when the thaw arrives. In prolonged cold weather several weeks' accumulation of snow may occur in upland areas especially (indicated by precipitation values above zero when the mean temperature for the square is zero or less). It may be reasonable in this situation to sum the weekly EPs and use that as the likely snow-melt figure when the thaw arrives.

For the annual crops which are harvested a bare soil situation is assumed to hold on the day of harvest. On the harvest day the fractions of available water in the two reservoirs (easily available and less easily available) to the maximum available water are calculated. These fractions are assumed to apply to the bare soil which follows harvest so as to calculate the values of water in the two reservoirs for bare soil. The remaining SMD, known as the SUBSMD, remains until the bare soil model reaches zero SMD after which any further rain can go to reduce the SUBSMD. When the SUBSMD has been reduced to zero then any further positive values of (rain – evaporation) are called EP. When a crop is sown there is a period of bare soil to be followed by a crop and soil combination. On the day that the crop emerges there is a transfer of the current bare soil SMD such that all of the bare soil SMD is assumed to reside in the easily available reservoir of the crop. If this exceeds the maximum quantity of easily available water then the remainder is given over to the reservoir of water which is more difficult to extract.

After emergence of the crop the roots begin to grow and the size of the soil moisture reservoirs increases. However, if SUBSMD is above zero then there is a transfer of SMD to the crop SMD and SUBSMD decreases.

The modelling of SMD and EP described in this section relies on the field capacity concept. This has often been criticized because some soils rarely attain the zero drainage steady state which this assumes. In particular the drying front in soils in the spring and summer is characterized by a 'zero flux plane' above which there is upward movement of soil water and below which there is continued drainage from the soil profile. The concept of SMD which MORECS uses is most closely represented by the situation in spring and early summer for the spring-sown crops as the depth of rooting steadily increases. In effect the SMD is for the depth of soil above the zero flux plane. With perennial crops such as trees MORECS calculates its SMD for the whole depth of soil occupied by roots which might well include soil both above and below the zero flux plane. In this case it may be that there is loss of water by drainage from the base of the profile and also evaporation from the surface and trees. MORECS ignores the drainage when calculating the SMD.

The calculation of EP assumes that there is a rapid adjustment of the soil water profile with the excess water rapidly draining to the base of the profile. In soils which drain only slowly there will be slow drainage out of the profile perhaps for several weeks after the rainfall event. Many experiments have shown that drainage continues into early summer in some soils even when the SMD has become substantial near the surface. In all cases the EP values which MORECS calculates should be regarded as the maximum amount of water which could drain through the upper profile above the zero flux plane, but with the possibility that it might take some weeks to do so.

4.5.3 Calculation of real land use values of PE, AE, SMD and EP

Real land-use values of PE, AE, SMD and EP are calculated for each square by using the percentage of the various land uses in each square (Annexe B gives typical values). The various outputs for each individual crop are multiplied by the percentage for the land use and summed to give a real land-use value. The real land-use types are related to the individual crops used in MORECS according to Table 4.5.2.

Table 4.5.2. Relationship between real land use and MORECS surface types

Real land use	MORECS outputs
1. Impervious urban	Urban
2. Open water	Open water
3. Riparian	Riparian
4. Rock	Rock
5. Conifers	Conifers
6. Heather, gorse	Upland
7. Permanent grass	Grass
8. Deciduous trees	Deciduous trees
9. Orchards	Orchards
10. Rough grazing	Upland
11. Cereals	0.6 × winter wheat + 0.25 × winter barley + 0.15 × spring barley
12. Potatoes	(Main crop + earlies)/2
13. Temporary grass	Grass
14. Fallow	Bare soil

4.6 MORECS information and products

The basic approach with providing MORECS information is to supply what the customer wants and is prepared to pay for. The traditional national maps showing the square grid are still available on a weekly basis from the Wednesday. These may show the basic weather variables such as rainfall or sunshine hours as well as PE, AE, SMD and EP for any crop (and real land-use) on any of the three soil types. The country has also been subdivided into regions and maps which show any variable can be provided for each region. Tables of data can also be provided for any squares as requested. The single-site version can produce a stream of daily or weekly data for any site with a good record of rainfall which is available on The Met. Office's computer system. Alternatively a customer-supplied sequence of daily rainfall could be used. A MORECS 2.0 climatology for the squares for the period 1961–90 is available for grass growing in median AWC soil. Long-period climatologies for any crop and soil can also be provided using single-site MORECS provided a suitably long period of weather data is available.

Examples of the output are in Annexe C.

4.7 Comparisons between MORECS 1.0 and MORECS 2.0

A comparison between the two versions is at Annexe E.

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Our thanks are due to many people who helped formulate ideas, but particular thanks are to J Ashcroft for deriving the land uses for each square from the original data sets, and to K Adamson who painstakingly traced woodland areas from maps. The new soils information for the squares was provided by RJA Jones who also drew our attention to the newer ideas in soil water extraction. J Finch provided satellite land cover data and R Harding, R Ragab and J Cain provided much useful information for MORECS improvements.

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* Available from the National Meteorological Library, Bracknell, UK

Annexe A
Dates assumed for crop development

This annexe gives the dates for each grid square for sowing, harvesting, etc. of the various crops. Intermediate stages are determined from these year days using the information given in Table A1. The dates are expressed as '1 July' or else as a year day (1 = 1 January) so that for example 1 July = day 182 (Table A2).

Table A1. Year days for emergence etc.

Crop	day of sowing (d_s)	Start of spring growth, or emergence (d_e)	day full cover is reached (d_f)	day of harvest (d_h)
Spring barley	*	$d_s + 15$	$d_h - 60$	*
Winter wheat	–	15 Oct. (emergence) $d_h - 155$	$d_h - 60$	*
Winter barley	–	15 Oct (emergence) $d_h - 145$	$d_h - 60$	*
Early potatoes	*	$d_s + 25$	$d_s + 90$	*
Main crop potatoes	*	$d_s + 25$	$d_s + 90$	*
Sugar beet	*	$d_s + 64$	$d_s + 101$	*
Oil-seed rape	1 Sept.	dates are calculated by the model		

* dates obtained from the attached maps (Figs A1–A8)

Orchards and deciduous trees are treated by assuming that 40 days elapse between bud burst and full cover, and also between the onset of autumn senescence and complete leaf fall.

As an example for spring barley growing in square 94 we have the following dates

	Year day	Date
Sown	80	21 March
Emerged	95	5 April
Full cover	176	25 June
Harvest	236	24 August

Table A2. Date to day of year

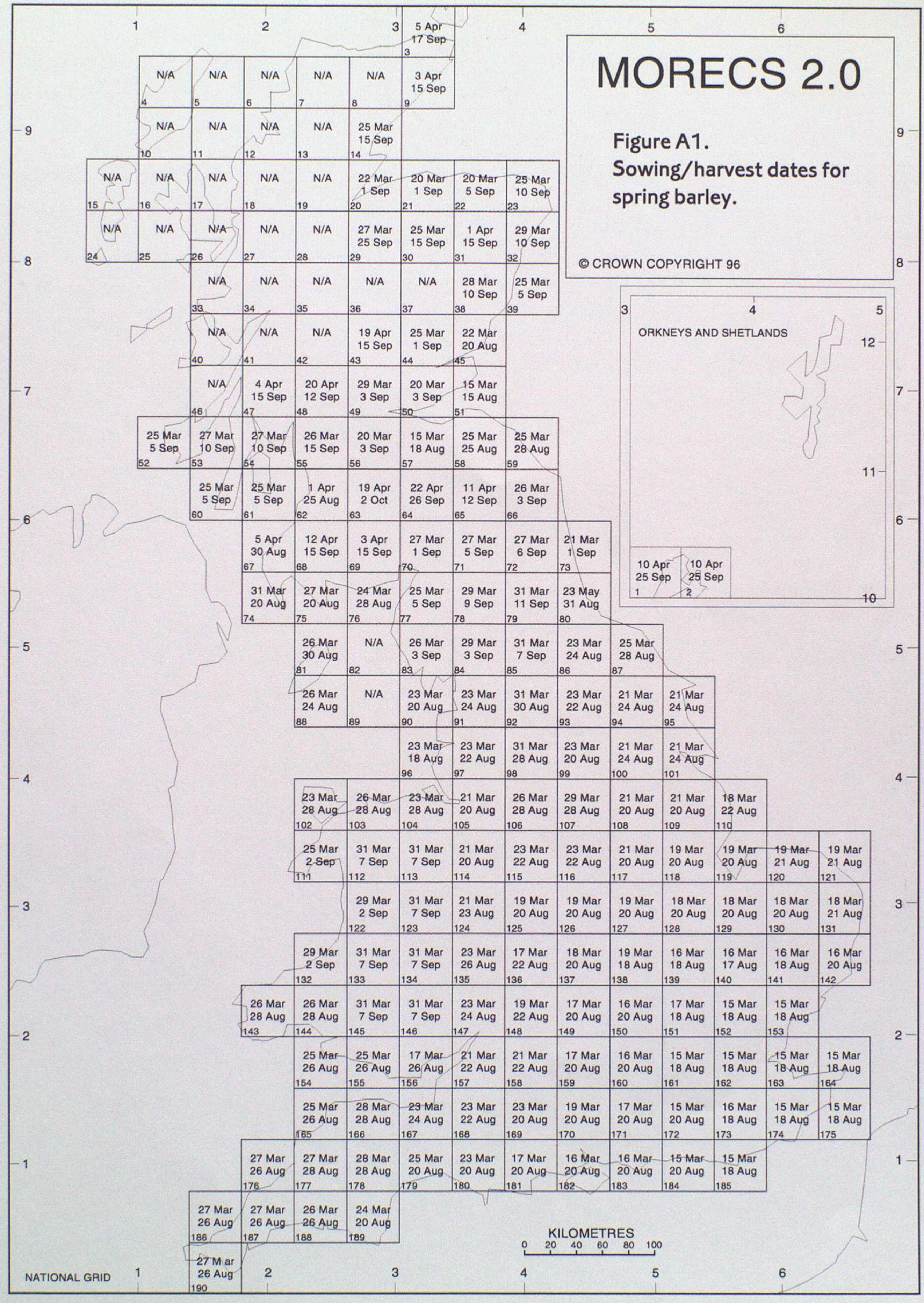
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Date
1	1	32	60	91	121	152	182	213	244	274	305	335	1
2	2	33	61	92	122	153	183	214	245	275	306	336	2
3	3	34	62	93	123	154	184	215	246	276	307	337	3
4	4	35	63	94	124	155	185	216	247	277	308	338	4
5	5	36	64	95	125	156	186	217	248	278	309	339	5
6	6	37	65	96	126	157	187	218	249	279	310	340	6
7	7	38	66	97	127	158	188	219	250	280	311	341	7
8	8	39	67	98	128	159	189	220	251	281	312	242	8
9	9	40	68	99	129	160	190	221	252	282	313	343	9
10	10	41	69	100	130	161	191	222	253	283	314	344	10
11	11	42	70	101	131	162	192	223	254	284	315	345	11
12	12	43	71	102	132	163	193	224	255	285	316	346	12
13	13	44	72	103	133	164	194	225	256	286	317	347	13
14	14	45	73	104	134	165	195	226	257	287	318	348	14
15	15	46	74	105	135	166	196	227	258	288	319	349	15
16	16	47	75	106	136	167	197	228	259	289	320	350	16
17	17	48	76	107	137	168	198	229	260	290	321	351	17
18	18	49	77	108	138	169	199	230	261	291	322	352	18
19	19	50	78	109	139	170	200	231	262	292	323	353	19
20	20	51	79	110	140	171	201	232	263	293	324	354	20
21	21	52	80	111	141	172	202	233	264	294	325	355	21
22	22	53	81	112	142	173	203	234	265	295	326	356	22
23	23	54	82	113	143	174	204	235	266	296	327	357	23
24	24	55	83	114	144	175	205	236	267	297	328	358	24
25	25	56	84	115	145	176	206	237	268	298	329	359	25
26	26	57	85	116	146	177	207	238	269	299	330	360	26
27	27	58	86	117	147	178	208	239	270	300	331	361	27
28	28	59	87	118	148	179	209	240	271	301	332	362	28
29	29		88	119	149	180	210	241	272	302	333	363	29
30	30		89	120	150	181	211	242	273	303	334	364	30
31	31		90		151		212	243		304		365	31

Figs A1 to A8 give the dates of the various crop stages. Information for squares in Northern Ireland is expected to appear in the future (Fig. A9) and cropping date details are as in Table A3.

Table A3. Cropping date details for Northern Ireland (day of year for: s = sowing, h = harvest, e = emergence, f = foliation, d = defoliation)

SQUARE	S barley		W wheat		W barley		E potatoes	
	s	h	e	h	e	h	s	h
191	90	245	288	240	288	222	60	170
192	90	245	288	240	288	222	60	170
193	90	245	288	240	288	222	60	170
194	95	255	288	250	288	232	70	180
195	95	255	288	250	288	232	70	180
196	90	245	288	240	288	222	70	180
197	85	240	288	235	288	217	60	170
198	95	255	288	250	288	232	70	180
199	93	255	288	250	288	232	70	180
200	90	245	288	240	288	222	60	170
201	85	240	288	235	288	217	60	170

SQUARE	M potatoes		S beet		Deciduous		Orchards	
	s	h	s	h	f	d	f	d
191	95	274	91	298	115	290	130	270
192	95	274	91	298	115	290	130	270
193	95	274	91	298	115	290	130	270
194	105	274	91	298	120	290	130	270
195	105	274	91	298	120	290	130	270
196	105	274	91	298	115	290	130	270
197	95	274	91	298	115	290	130	270
198	105	274	91	298	120	290	130	270
199	105	274	91	298	120	290	130	270
200	95	274	91	298	115	290	130	270
201	95	274	91	298	115	290	130	270

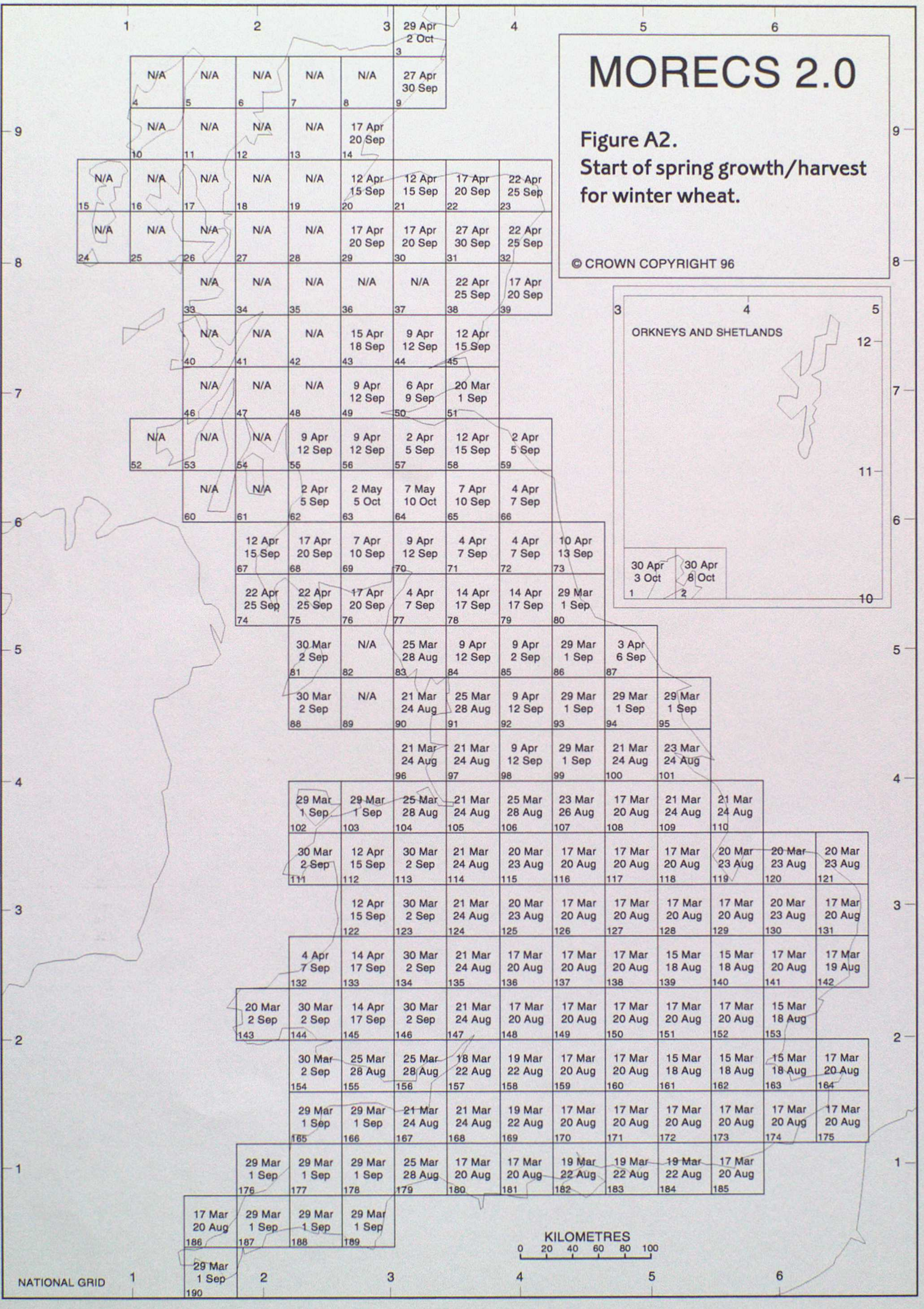


MORECS 2.0

Figure A1. Sowing/harvest dates for spring barley.

MORECS 2.0

Figure A2.
Start of spring growth/harvest for winter wheat.



MORECS 2.0

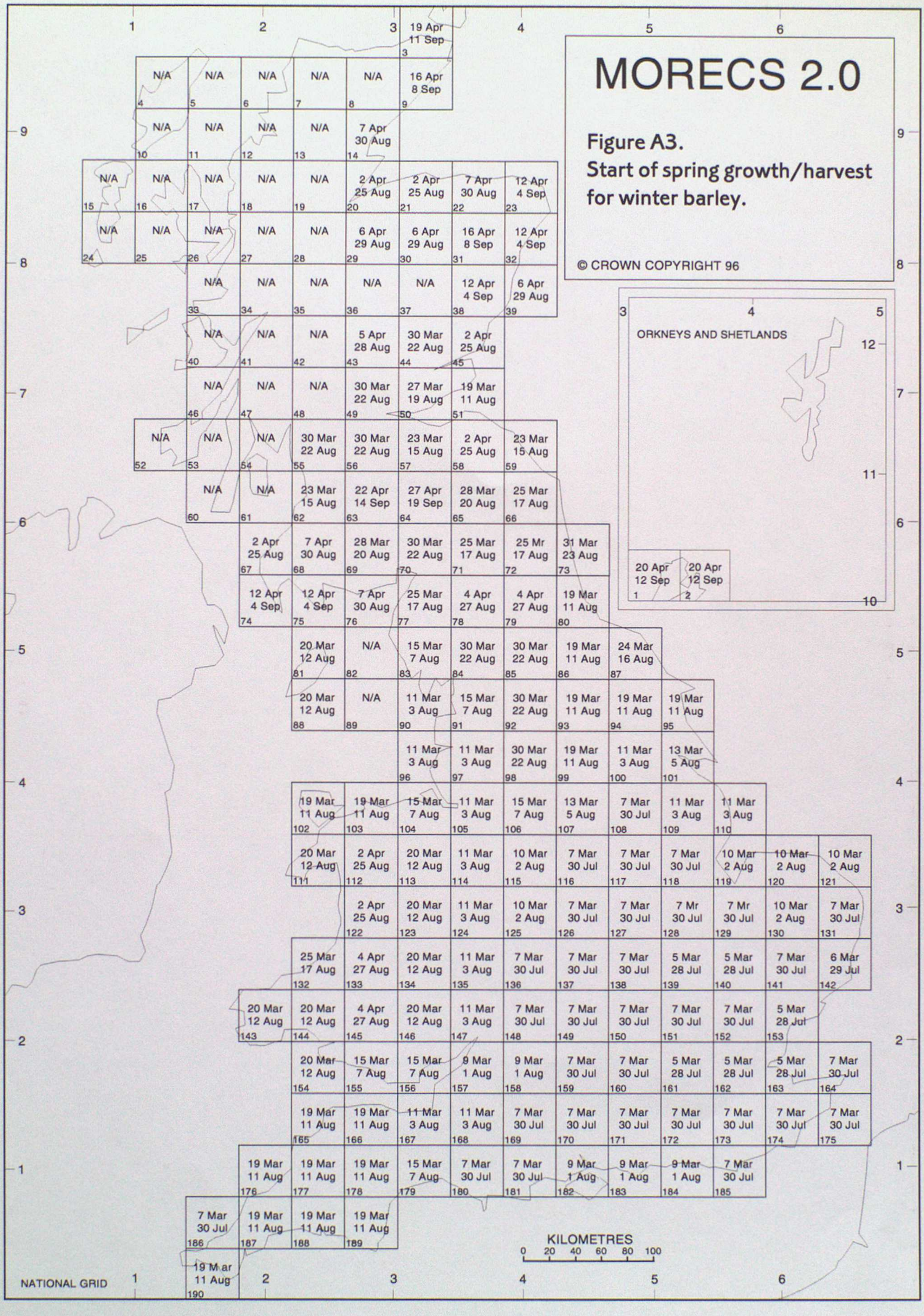
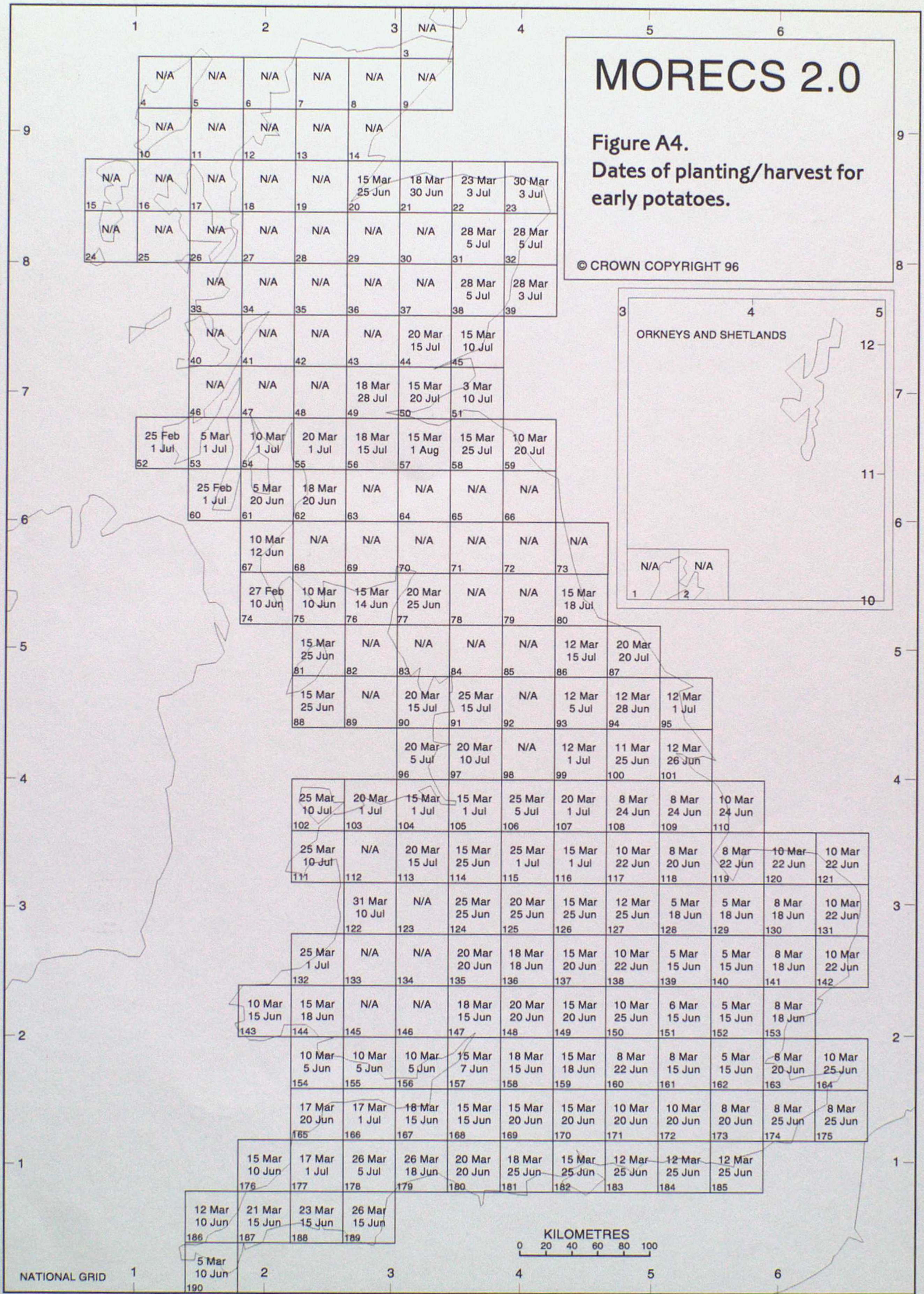
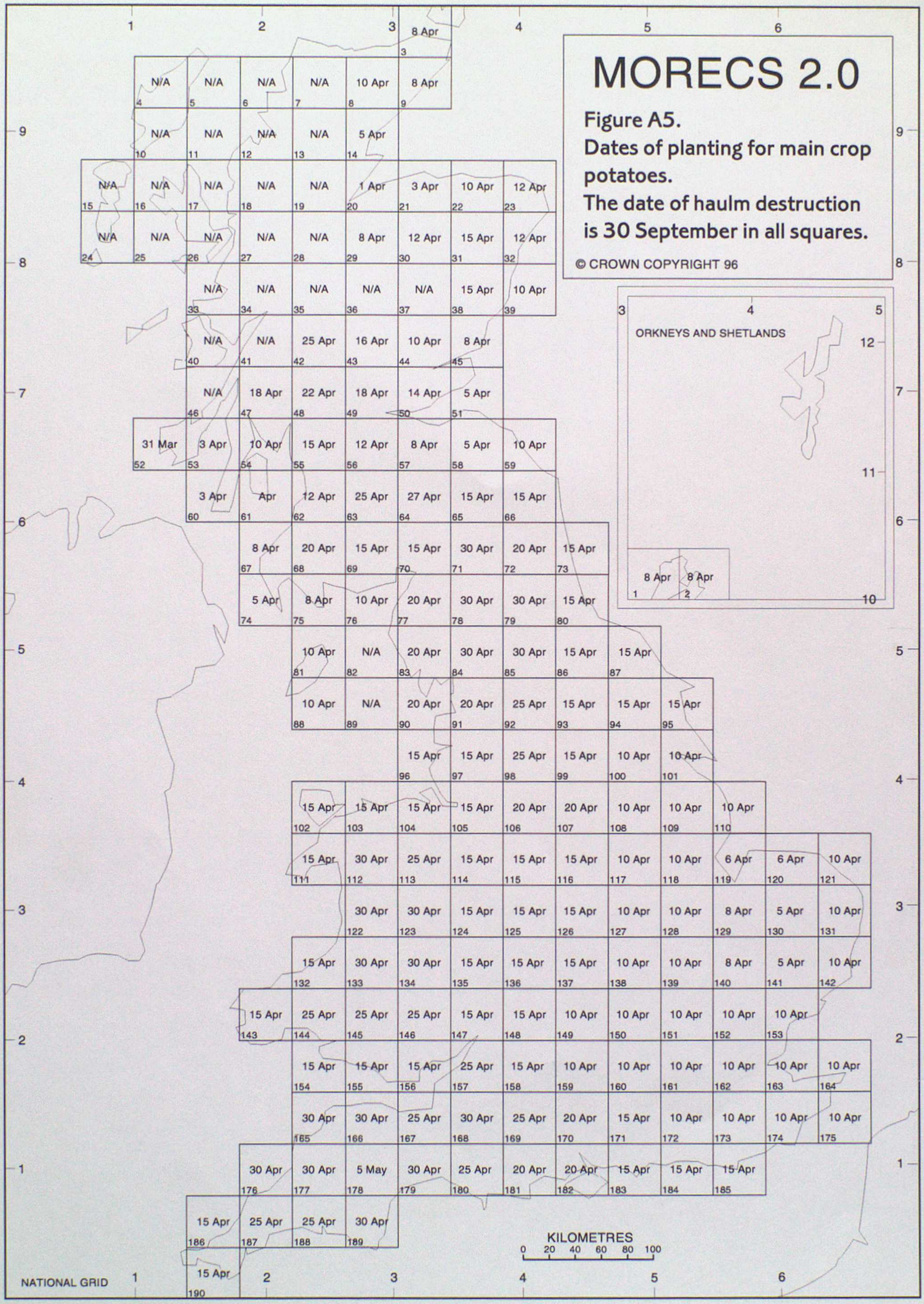


Figure A3.
Start of spring growth/harvest for winter barley.

MORECS 2.0

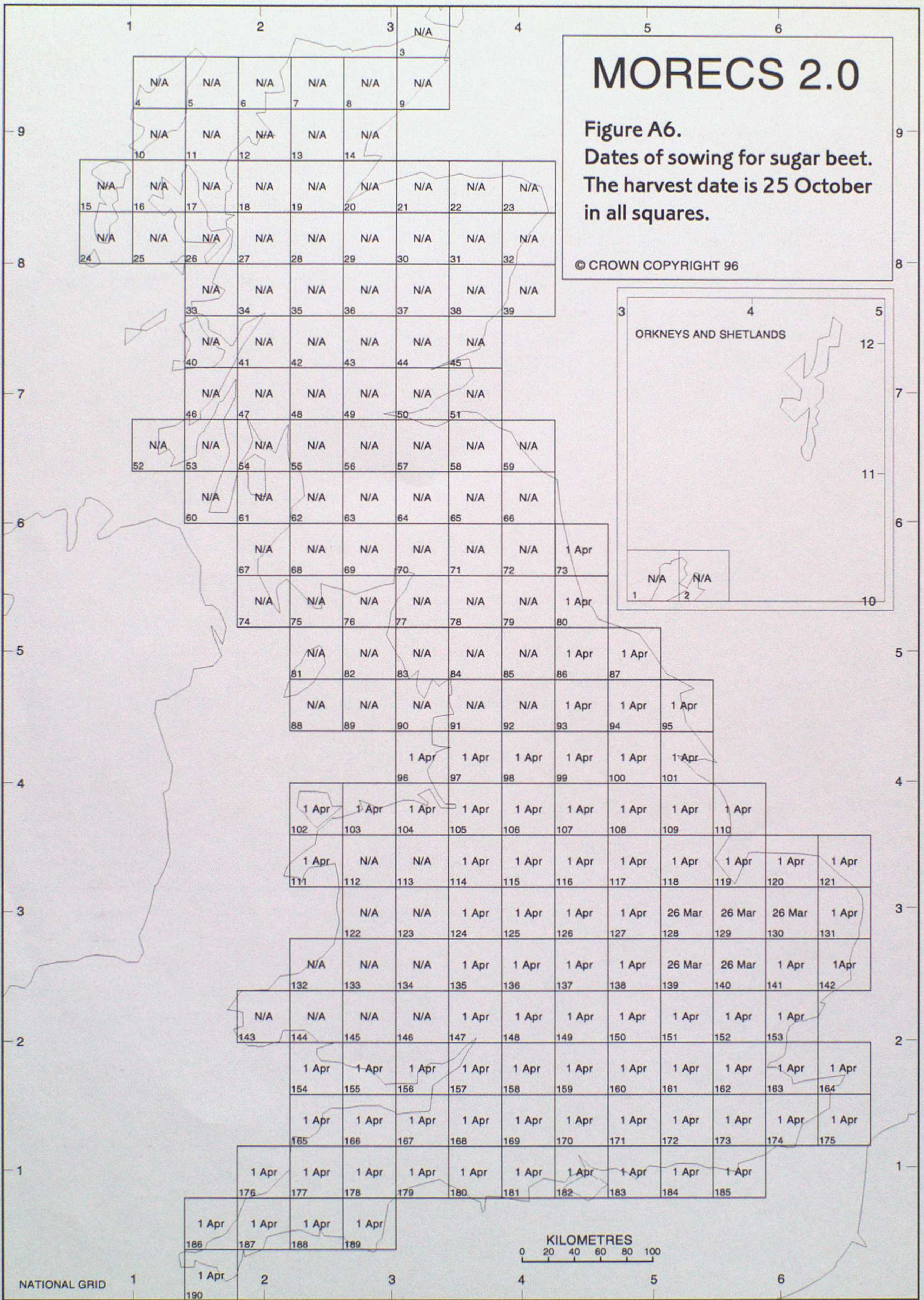
Figure A4.
Dates of planting/harvest for early potatoes.





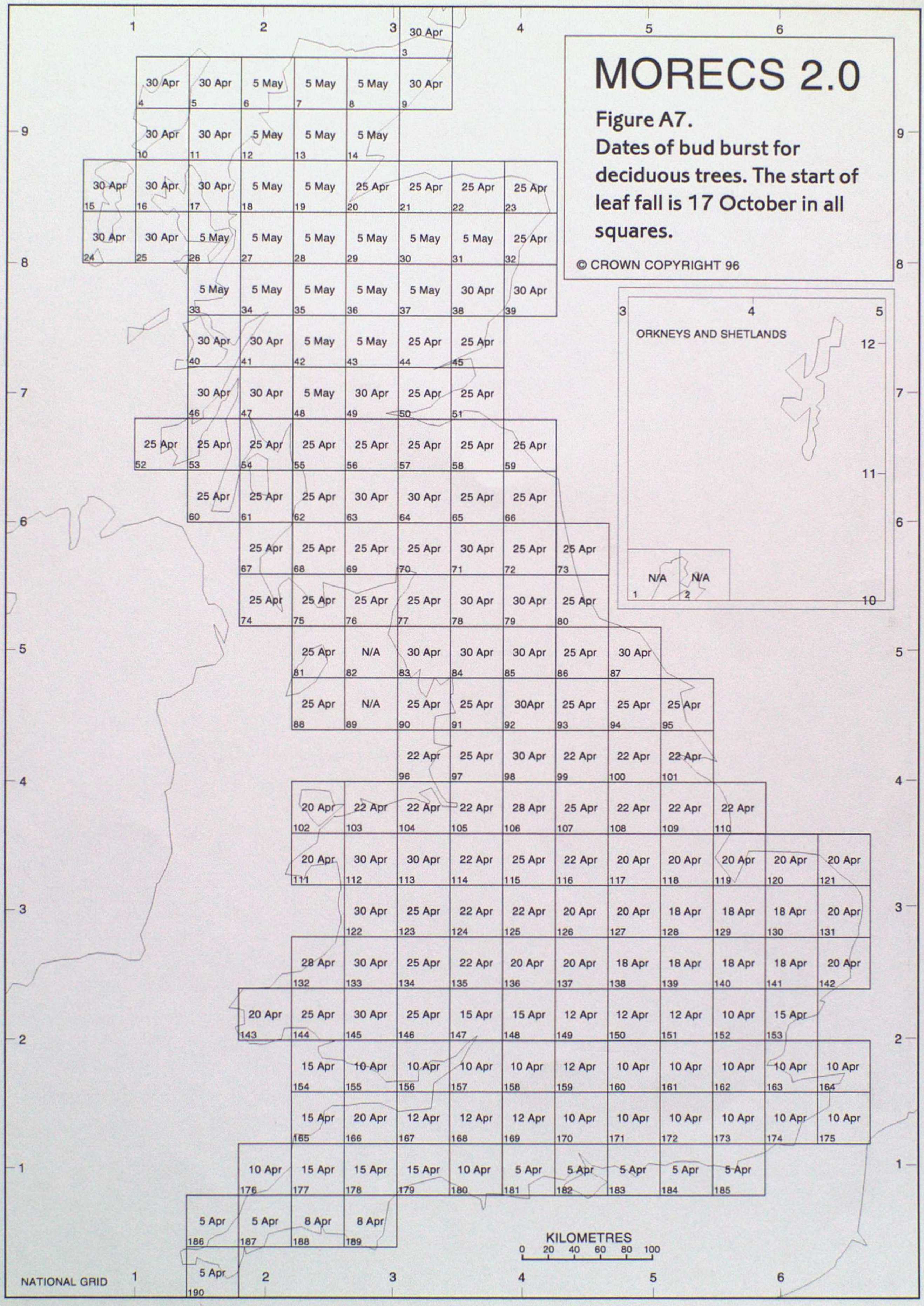
MORECS 2.0

Figure A5.
Dates of planting for main crop potatoes.
The date of haulm destruction is 30 September in all squares.



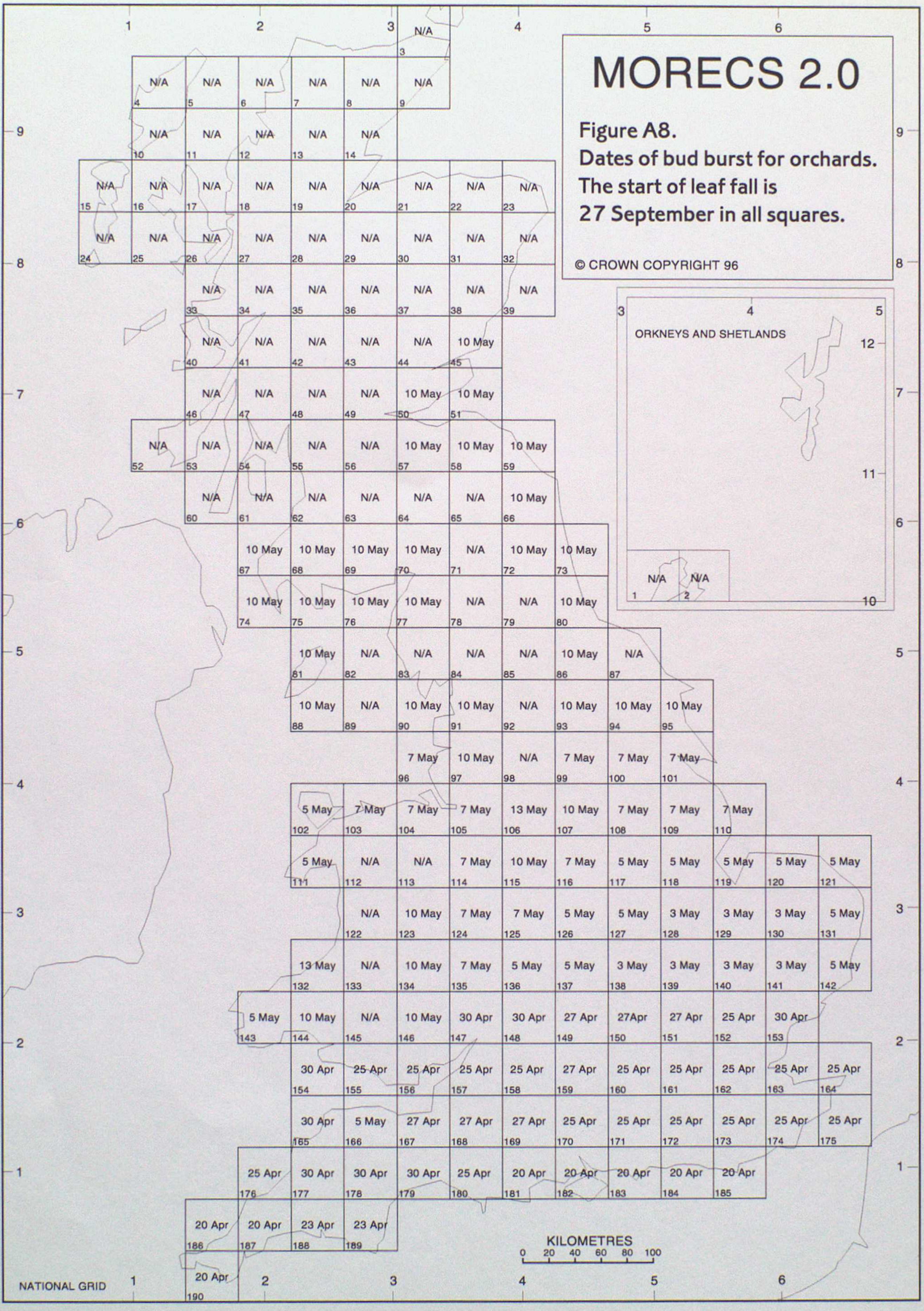
MORECS 2.0

Figure A6.
Dates of sowing for sugar beet. The harvest date is 25 October in all squares.



MORECS 2.0

Figure A7.
Dates of bud burst for deciduous trees. The start of leaf fall is 17 October in all squares.



MORECS 2.0

Figure A8.
Dates of bud burst for orchards.
The start of leaf fall is
27 September in all squares.

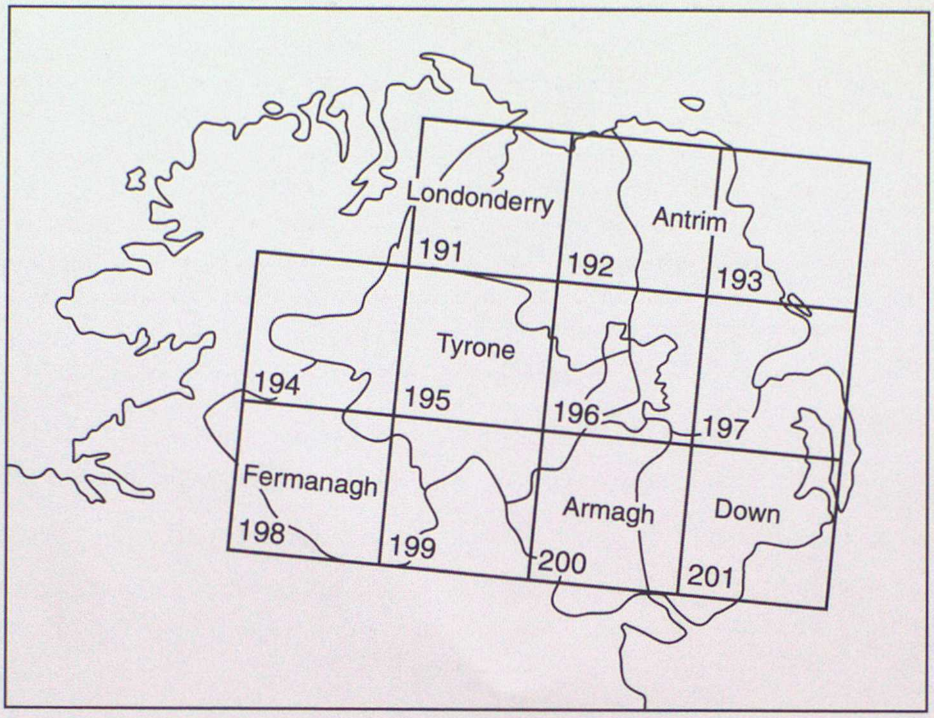


Figure A9.
Proposed MORECS squares in N. Ireland.
Note that the sides of the squares are parallel to the Irish grid.

Annexe B
Estimates of the percentage of land use types in each MORECS square

The revised land-use scheme is based upon the 1988 census of England and Wales (MAFF) and the similar one for Scotland (by DAFS). These census data, together with a land-use data set for the whole of UK, were provided by the University of Edinburgh computing services as a 5 km grid data set of the proportion under the different land uses for each 5 km square. The 5 km squares were aggregated to the 40 km squares which are used in MORECS to obtain the area within each square under each land use. These areas were then expressed as a percentage of the total land area within each square.

Woodland areas posed a particular problem since MORECS needs the separate areas of coniferous and deciduous woodland. At first estimates were obtained from the Ordnance Survey maps, but after this was done some satellite-derived areas (the situation as of about 1990) were obtained. It was finally decided to use the satellite data in preference to maps for the woodland areas.

Hence for each square the following areas of land use were found:

(1)	Urban	Direct from the land-use data set.
(2)	Open water	Direct from the land-use data set.
(3)	Riparian	From existing MORECS 1.0 land-use figures. (Riparian was found by estimating the area between rivers and 'the first contour'.)
(4)	Rock	From existing MORECS 1.0 figures.
(5)	Coniferous forest	From satellite data.
(6)	Deciduous trees	From satellite data.
(7)	Grass	Direct from the census data set.
(8)	Rough grazing	Direct from the land-use data set.
(9)	Orchards	From the census data set.
(10)	Cereals	The sum of the areas of winter wheat, winter barley and spring barley from the census data set.
(11)	Oil-seed rape	Direct from the census data set.
(12)	Potatoes	Direct from the census data set.
(13)	Sugar beet	Direct from the census data set.
(14)	Fallow (bare soil)	Direct from the census data set.

Corrections and adjustments

The pace of change in cropping patterns is such that it was considered desirable to correct some of the figures of the 1988 census to values more representative of the early 1990s. Some national areas of farm crops were available for England and Wales, plus Scotland for 1991 and for England in 1992. The percentage change in crop areas between 1988 and 1992 in England is as follows:

Winter wheat	+9%
Winter barley	–7%
Spring barley	–66%
Oil-seed rape	+19%
Fallow	–32%

In Scotland the corresponding figures from 1988 to 1991 are:

Winter wheat	+11%
Winter barley	–6%
Spring barley	–18%
Oil-seed rape	+20%

and in Wales for 1988–1991

Winter wheat	+20%
Winter barley	no change
Spring barley	–41%
Oil-seed rape	+57%

The 1988 census figures were corrected using these figures for each square in each country. The largest change was to spring barley in England.

By summing the separate 14 areas the total land area in the squares accounted for averaged 93%. Only 66% of one square in the Outer Hebrides was accounted for while one square in Wales came out as 130%. Final adjustments were made so that the total land area accounted for was 100%. First the non-agricultural land was apportioned between grass and rough grazing. For example, square 169 has 15.9% in this category, mainly in MoD land which was set to rough grazing. Square 161 has 17.4% non-agricultural land (probably parkland) and this was attributed to grass land use. Secondly, the rough grazing category was increased in moorland/coastal areas or in squares with much urban area. Thirdly, grassland was increased in areas with mainly pastoral farming, while the cereals area was increased in the mainly arable squares. A few squares in Surrey and Sussex had their woodland areas increased by 1–2% to allow for the numerous small areas of woodland which are a feature of the area. Most of the changes were between 4–8%, usually for grass, rough grazing or cereals.

Set-aside

The CEC rotational set-aside scheme in 1993 and 1994 required farmers to remove 15% of their land under cereals and oil-seed rape. This land could be allowed to regenerate a green cover naturally, or else be sown with grass or a non-food industrial crop. Surveys reported in the farming press showed that the options which were chosen varied a great deal, but that natural regeneration was the most popular. In MORECS this sort of set-aside is allocated to 'rough grazing'. About 15% of the set-aside area is sown to grass and 10% to industrial oil-seed rape. In MORECS these areas are allocated to 'grass' and 'oil-seed rape'.

Let C, O, G and R be the percentages areas of cereals, oil-seed rape, grass and rough grazing before the set-aside regime and C´, O´, G´ and R´ the areas after set-aside. Then if A is the area of set-aside:

$$A = 0.15\,(C + O)$$
$$C' = 0.85\,C$$
$$O' = 0.85\,O + 0.1\,A$$
$$G' = G + 0.15\,A$$
$$R' = R + 0.75\,A$$

In practice R´ was chosen to make the total land area equal to 100% in each square. For squares with less than 10% of cereals the changes were minimal and the calculation was only done for squares with more than this.

In summary the land use in each square is an attempt to reproduce the land use as of 1992 with an allowance for 15% set-aside. The uptake of the non-rotational set-aside scheme is not known at the time of writing and is not included. For cropping year 1995–96 the set-aside figure looks likely to fall to 10%, but this is ignored for the present.

The following table shows the typical per cent of each crop or land use in nine main groupings of land use which occur in the UK.

Land use group and squares	Typical land use (see key)													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Rough grazing (4–19, 24–30, 33–37, 40–43, 46–48, 52, 53, 63)	0	1	4	1	2	2	5	85	0	0	0	0	0	0
Grass and rough grazing (1–3, 78, 79, 84, 85, 92, 191–195)	0	1	3	0	2	1	45	45	0	3	0	0	0	0
Grass, rough grazing and trees (20–22, 38, 49, 54, 55, 60–62, 64–71, 83, 103, 106, 112, 122, 133, 145, 146, 154)	0	1	2	0	15	5	27	40	0	8	1	0	0	1
Grass, rough grazing and cereals (23, 31, 32, 39, 44, 45, 50, 56–58, 66, 72, 87, 88)	1	0	1	0	4	4	40	25	0	20	3	1	0	0
Grass (74–77, 81, 90, 91, 102, 111, 113, 115, 123, 132, 134, 143, 144, 156, 157, 165–168, 176–180, 186–190, 196, 198–201)	2	0	2	0	2	3	65	15	0	10	0	1	0	0
Grass and arable (51, 59, 86, 93, 96, 97, 105, 107, 114, 116, 117, 124, 126, 127, 131, 135–138, 147–150, 158–160, 163, 169, 174, 175, 184, 197)	2	0	2	0	2	2	30	15	0	3	4	4	1	3
Grass, arable and trees (170–173, 181–183, 185)	12	0	2	0	5	15	34	10	0	15	3	1	0	3
Arable (94, 95, 100, 101, 108–110, 118–121, 120, 121, 128–130, 139–142, 151–153)	5	0	2	0	2	4	12	12	0	44	6	3	6	4
Urban (73, 80, 98, 99, 104, 125, 161, 162, 164)	40	0	2	0	1	6	20	10	0	15	2	1	1	2

Key

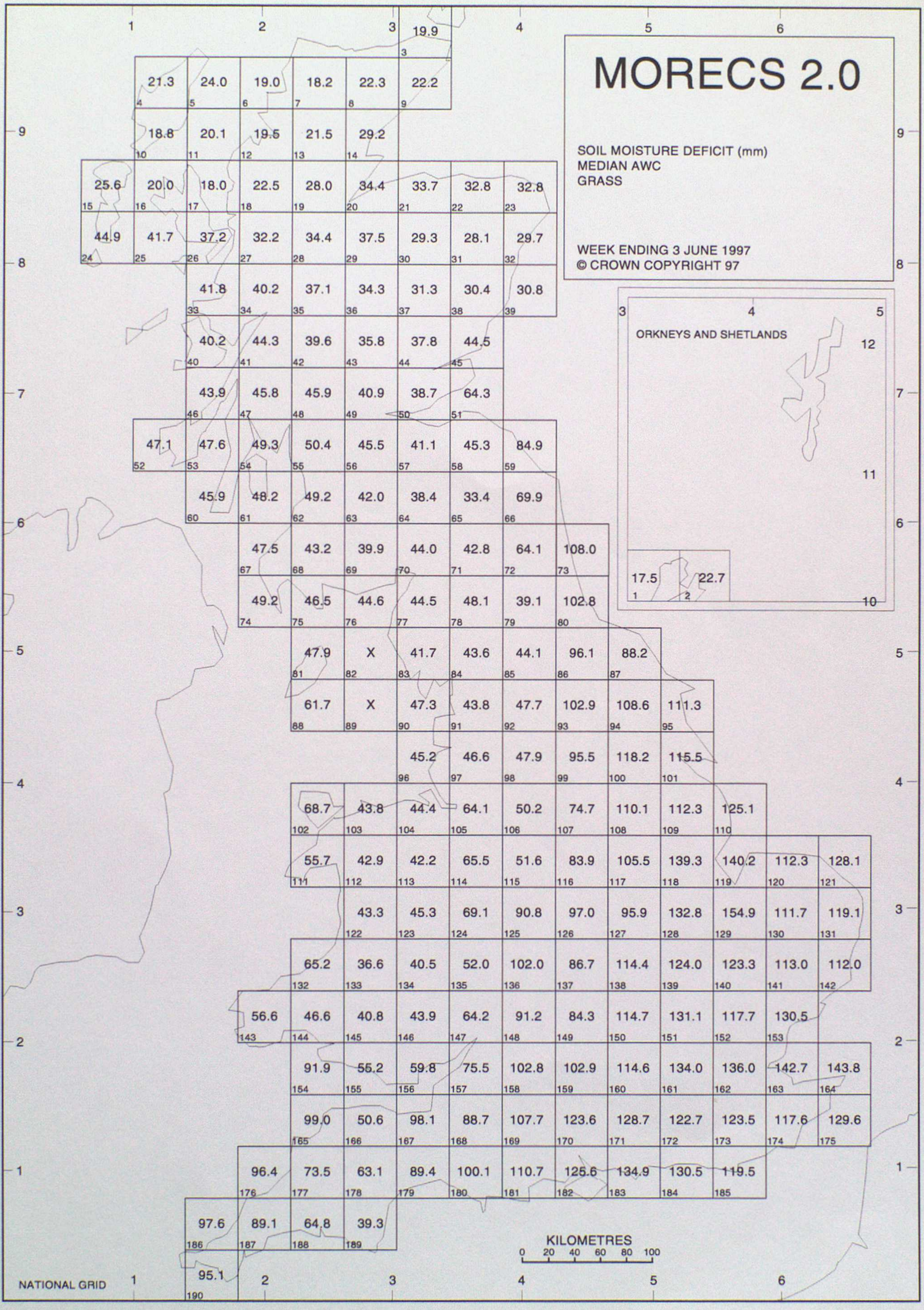
(1) Urban
(2) Open water
(3) Riparian
(4) Rock
(5) Conifers
(6) Deciduous trees
(7) Grass
(8) Rough grazing (includes set-aside)
(9) Orchards
(10) Cereals
(11) Oil-seed rape
(12) Potatoes
(13) Sugar beet
(14) Fallow (bare soil)

Annexe C
Examples of MORECS outputs

MORECS 2.0

SOIL MOISTURE DEFICIT (mm)
MEDIAN AWC
GRASS

WEEK ENDING 3 JUNE 1997

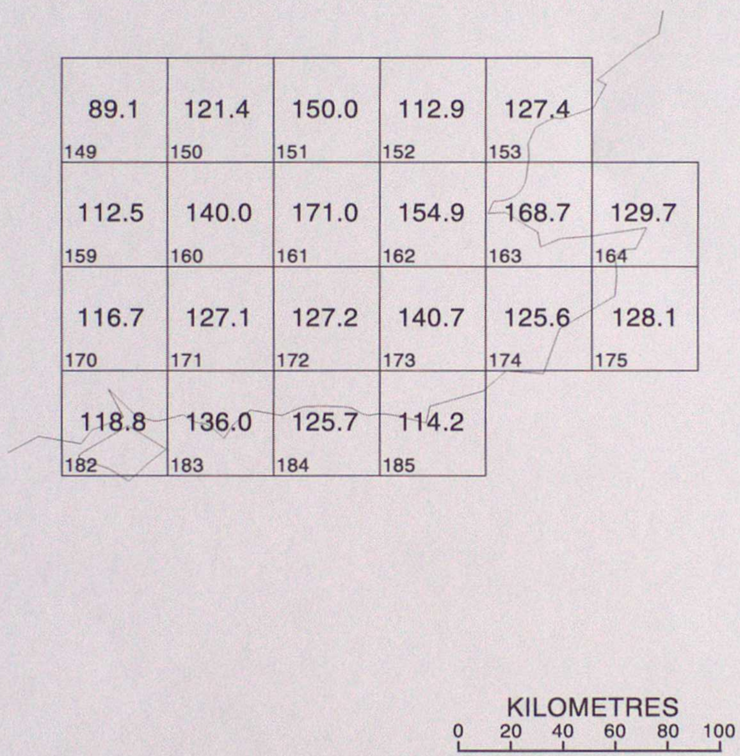


MORECS 2.0

SOIL MOISTURE DEFICIT (mm)
HIGH AWC
REAL LAND USE

SOUTHEAST ENGLAND

WEEK ENDING 3 JUNE 1997



FARM ADVISORY SERVICES TEAM LTD

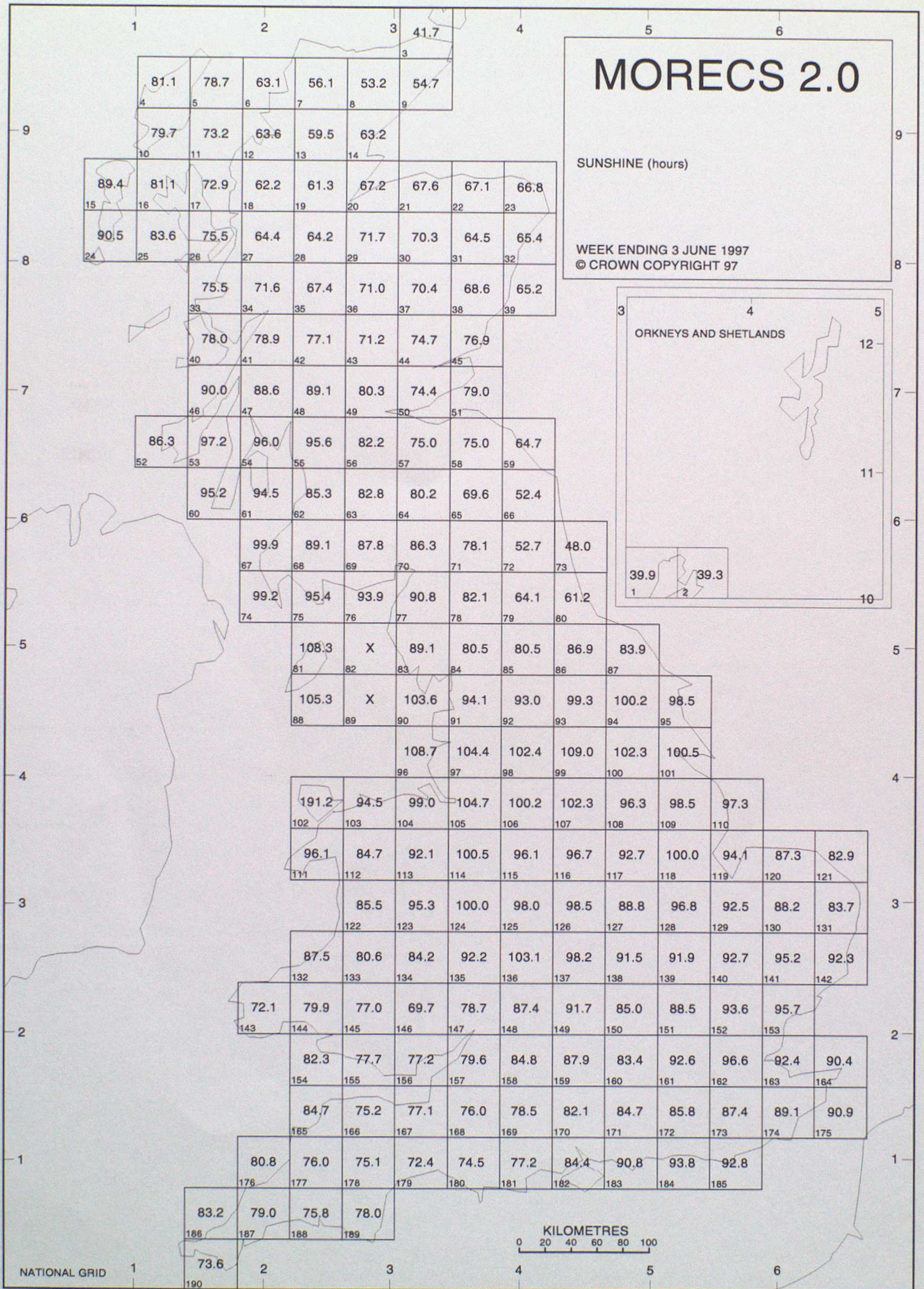
MORECS 2.0 DATA FOR WEEK ENDING 03/06/97

SOIL : MEDIAN AWC   CROP : ORCHARDS

ELEMENT SQUARE NO	SMD
129	202.3
131	132.5
147	64.5
153	158.1
174	125.2

KEY

SMD : SOIL MOISTURE DEFICIT (mm)


MORECS 2.0
SUNSHINE (hours)
WEEK ENDING 3 JUNE 1997
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ORKNEYS AND SHETLANDS
39.9 1
39.3 2
41.7 3
81.1 4
78.7 5
63.1 6
56.1 7
53.2 8
54.7 9
79.7 10
73.2 11
63.6 12
59.5 13
63.2 14
89.4 15
81.1 16
72.9 17
62.2 18
61.3 19
67.2 20
67.6 21
67.1 22
66.8 23
90.5 24
83.6 25
75.5 26
64.4 27
64.2 28
71.7 29
70.3 30
64.5 31
65.4 32
75.5 33
71.6 34
67.4 35
71.0 36
70.4 37
68.6 38
65.2 39
78.0 40
78.9 41
77.1 42
71.2 43
74.7 44
76.9 45
90.0 46
88.6 47
89.1 48
80.3 49
74.4 50
79.0 51
86.3 52
97.2 53
96.0 54
95.6 55
82.2 56
75.0 57
75.0 58
64.7 59
95.2 60
94.5 61
85.3 62
82.8 63
80.2 64
69.6 65
52.4 66
99.9 67
89.1 68
87.8 69
86.3 70
78.1 71
52.7 72
48.0 73
99.2 74
95.4 75
93.9 76
90.8 77
82.1 78
64.1 79
61.2 80
108.3 81
X 82
89.1 83
80.5 84
80.5 85
86.9 86
83.9 87
105.3 88
X 89
103.6 90
94.1 91
93.0 92
99.3 93
100.2 94
98.5 95
108.7 96
104.4 97
102.4 98
109.0 99
102.3 100
100.5 101
191.2 102
94.5 103
99.0 104
104.7 105
100.2 106
102.3 107
96.3 108
98.5 109
97.3 110
96.1 111
84.7 112
92.1 113
100.5 114
96.1 115
96.7 116
92.7 117
100.0 118
94.1 119
87.3 120
82.9 121
85.5 122
95.3 123
100.0 124
98.0 125
98.5 126
88.8 127
96.8 128
92.5 129
88.2 130
83.7 131
87.5 132
80.6 133
84.2 134
92.2 135
103.1 136
98.2 137
91.5 138
91.9 139
92.7 140
95.2 141
92.3 142
72.1 143
79.9 144
77.0 145
69.7 146
78.7 147
87.4 148
91.7 149
85.0 150
88.5 151
93.6 152
95.7 153
82.3 154
77.7 155
77.2 156
79.6 157
84.8 158
87.9 159
83.4 160
92.6 161
96.6 162
92.4 163
90.4 164
84.7 165
75.2 166
77.1 167
76.0 168
78.5 169
82.1 170
84.7 171
85.8 172
87.4 173
89.1 174
90.9 175
80.8 176
76.0 177
75.1 178
72.4 179
74.5 180
77.2 181
84.4 182
90.8 183
93.8 184
92.8 185
83.2 186
79.0 187
75.8 188
78.0 189
73.6 190
KILOMETRES
0 20 40 60 80 100
NATIONAL GRID

Annexe D

Estimates of the typical available water capacity for grass in each MORECS square

The values are for the median, the ten percentile and ninety percentile AWC in each square together with the per cent (P) which is freely available.

AWC range (mm)	Squares
	Median
<= 120	120, 127, 130, 138, 141, 142, 148, 152, 165, 186–189
121–130	9, 14, 19–23, 32, 38, 39, 44, 45, 50, 51, 57–59, 62, 63, 66, 67, 69, 72–78, 80, 82, 86, 88, 90, 93, 97–99, 102–109, 113–117, 124–126, 131, 132, 136, 137, 139, 140, 143, 144, 147, 149, 154, 156–158, 166–168, 176–178, 190, 196, 197, 200, 201
131–140	1–8, 10–13, 15–18, 24, 25, 27–31, 33–37, 42, 43, 46–49, 52–56, 60, 79, 84, 87, 91, 94–96, 100, 101, 111, 123, 134, 145, 146, 150, 151, 153, 155, 159–162, 169, 171, 172, 174, 179–182, 191–195, 198, 199
>140	26, 40, 41, 61, 64, 65, 68, 70, 71, 81, 83, 85, 92, 110, 112, 118, 119, 121, 122, 128, 129, 133, 135, 163, 164, 170, 173, 175, 183–185

P lies between 52 and 74%

AWC range (mm)	Squares
	Ten percentile
<= 90	90, 96, 125, 142, 154, 187
91–100	108, 148, 149, 157, 158, 168, 171
101–110	7, 8, 13, 16–18, 27–31, 34–37, 42, 43, 48, 78, 84, 87, 98, 99, 103–107, 113, 114, 116–118, 120, 122, 124, 127, 128, 130, 143, 144, 155, 165, 167, 178, 186, 189, 191
>110	1–6, 9–12, 14, 15, 19–26, 32, 33, 38–41, 44–47, 49–77, 79–83, 85, 86, 88, 91–95, 97, 100–102, 109–112, 115, 119, 121, 123, 126, 129, 131–141, 145–147, 150–153, 156, 159–164, 166, 169, 170, 172–177, 179–185, 188, 190, 192–201

P lies between 51 and 73%

AWC range (mm)	Squares
	Ninety percentile
<= 150	9, 14, 19–23, 32, 38, 39, 44, 45, 50, 51, 59, 67, 73–76, 80, 82, 86, 93, 94, 99, 102, 107, 109, 114–117, 120, 124–127, 130, 132, 136–139, 141–143, 147–153, 156–162, 165, 169–171, 177, 178, 181–184, 186, 188–190, 197
151–200	1–6, 10–12, 15, 24, 25, 33, 46, 47, 52–54, 57, 58, 60, 62, 63, 66, 69, 72, 77, 87–90, 95, 101, 103–105, 108, 110, 111, 113, 121, 123, 128, 131, 134, 135, 140, 144–146, 154, 155, 163, 164, 166–168, 172–176, 179, 180, 185, 187, 192–195, 200, 201
201–250	26, 40, 41, 61, 68, 70, 81, 83, 96, 97, 100, 106, 118, 119, 122, 129
>250	7, 8, 13, 16–18, 27–31, 34–37, 42, 43, 48, 49, 55, 56, 64, 65, 71, 78, 79, 84, 85, 91, 92, 98, 112, 133, 191, 196, 198, 199

P lies between 62 and 81%

Annexe E
A comparison between MORECS 1 and 2

Several changes have been made in producing MORECS 2 which in summary include the following:

(a) Revised total available water capacity to reflect the actual soils.
(b) Revised proportion of the soil water which is freely available.
(c) Revised leaf area models for the winter cereals.
(d) Revised canopy resistance for upland.
(e) Set-aside and oil-seed rape introduced as new crops.

A comparison between the two versions has been made to show these differences. The single-site version of the model has been used with 5 years of weather data from the site at Newport in Shropshire. The years between 1987 and 1991 were chosen to show the effects of cool, wet summers (as in 1987 and 1988) and the warm, dry weather in 1989, 1990 and 1991. Because grass is the most widely used crop when considering MORECS data, a detailed comparison is made for this land use. Comparisons are also made for winter wheat, upland and bare soil. Some data are also given for oil-seed rape, since although this crop was not present in MORECS 1, the behaviour of the model in two contrasting years is given.

Grass

Potential Evapotranspiration

No changes have been made to the calculation of PE for grass and this is shown in Fig. E1 where the 5 years of daily PE values are plotted for both versions of MORECS. Small differences of 0.1 mm are found which are due to rounding errors in the computer and the correlation is nearly perfect as should be the case.

Soil Moisture Deficit (medium/median soil)

In Fig. E2 the SMDs for both versions of MORECS are plotted. Newport lies in square 114 and the median soil has an AWC for grass of 122 mm, just 3 mm less than the MORECS 1 value for medium soil. In the three very dry years the SMD reaches the maximum possible value and the Figure shows how MORECS 1 reaches 125 mm when MORECS 2 is at 122 mm. During the weeks prior to reaching the maximum SMD the SMD for MORECS 2 tends to be greater than MORECS 1 because a greater proportion of the available water can be transpired at the potential rate. This is especially clear in the wetter year of 1988 because the SMD remained longer in the range 50–100 mm when the differences in AE tend to be greatest. The MORECS 1 AE starts to become less than PE once the SMD exceeds 50 mm, but from 50 to about 80 mm SMD the transpiration from MORECS 2 is still at the potential rate. In the wettest year of 1987 the SMD rarely exceeded 60 mm and the differences in SMD were very small.

Excess Rainfall (medium/median soil)

Figs E3 and E4 show the daily values of excess rain for both versions. They are almost identical.

Soil Moisture Deficit (low AWC/ten-percentile soil)

In MORECS 1 the low AWC soil for grass has 94 mm of available water while in MORECS 2 the ten-percentile soil in square 114 has 104 mm. In this case Fig. E5 shows that in the three dry years the maximum SMDs were reached, with MORECS 1 about 10 mm lower than MORECS 2. In 1988 MORECS 2 tended to have higher SMD throughout the summer and even in the wet year of 1987 the MORECS 2 SMD was often slightly more.

Excess Rainfall (low AWC/ten-percentile soil)

Figs E6 and E7 show that MORECS 1 has a few occasions with larger values of excess rain than MORECS 2. These days tend to be when the soil returns to field capacity in autumn because MORECS 1 usually returns to capacity a few days earlier. Over the 5-year period of the analysis MORECS 2 had nearly 39 mm less excess rain than version 1 (636.9 compared with 675.6 mm).

Actual Evaporation (low AWC/ten-percentile soil)

The difference in AE is shown in Fig. E8. A positive difference indicates that MORECS 2 has a higher AE. The many small differences, both positive and negative, equal to 0.1 mm are caused by rounding errors by the computer. The graph shows the effect of the higher proportion of the AWC which is available for transpiration in MORECS 2, especially in late spring and summer. There are two occasions when MORECS 1 AE is greater. On these occasions some rain had followed a dry period in which MORECS 2 had reached the maximum SMD, but MORECS 1 had not quite reached the limit. The rain which had fallen resided in the easily available portion and was transpired at the potential rate. MORECS 2 reached the maximum SMD a day before MORECS 1 so that on the next day MORECS 1 still had a little water to remove from the soil when the MORECS 2 AE was due to rainfall only.

Winter wheat

Potential Evapotranspiration

Fig. E9 shows the PE for winter wheat version 1 plotted against version 2. For the spring and summer part of the year the PEs are equal, but some differences occur in autumn because MORECS 2 has some leaf cover present whereas version 1 assumes a bare soil. This is shown as a thickening in the line of points for PE values below about 2 mm. The largest differences (about 0.2–0.3 mm) are on windy, mild days in November and December.

Soil Moisture Deficit (high AWC soil/90-percentile soil)

The 90-percentile soil in square 114 has an AWC for winter wheat of 134 mm while MORECS 1 set its high AWC soil at the rather larger value of 175 mm. In this case the SMD for MORECS 1 can reach higher values than version 2 (Fig. E10) in the dry summers. However, at more moderate SMDs between about 75 and 110 mm MORECS 2 SMDs are higher because the version 1 AE is less than the PE for deficits in this range.

Actual Evaporation

In Fig. E11 the effects of the different water availabilities at different ranges of SMD on the AE are shown. Here we see that MORECS 2 has higher AE (positive AE difference) when the SMD is in the range 75 to 110 mm. At these deficits MORECS 2 permits transpiration at the potential rate, but in MORECS 1 the AE becomes less than the PE. However, MORECS 1 has higher AE for SMD above 110 mm because of the higher AWC. The change between these two regimes is particularly clear for the three dry summers.

Excess Rainfall

Over the 5-year period MORECS 2 had 40.2 mm more excess rain than version 1 (670.3–630.1 mm). Most of this difference arose from an earlier return to field capacity after the dry summers for MORECS 2 (Figs E12 and E13).

Bare soil

Potential Evaporation

In Table 4.2.1 the variation of the albedo of bare soil was listed. It is allowed to vary in the same way in MORECS 1 and 2 such that the albedo depends on the AWC of the soil and also whether the surface is dry or wet. In MORECS it is assumed that bare soil is wet if more than 0.2 mm of rain has fallen. Fig. E14 shows a comparison between the PE values for MORECS 1 and 2 for the 5 years. Usually there is no difference between the two PEs, but occasionally the MORECS 2 PE is between 0.2 and 0.6 mm lower. This was traced to the adjustment of albedo depending upon the rainfall for the day. It would appear that MORECS 1 regarded 0.2 mm of rain as being above 0.2 (by the way that the number is represented in the computer). Hence on days with 0.2 mm of rain MORECS 1 has wet, bare-soil PE, but MORECS 2 has the dry, bare-soil PE, which is lower. Over the five years of the calculations this affected about 20 days when the PE was sufficiently large (above about 2 mm per day) so that a significant difference developed.

Soil Moisture Deficit

Fig. E15 compares the SMD for medium and median soil for the two versions. The different AWC values is the major difference here: MORECS 1 has a value of 20 mm while MORECS 2 recognizes that the median soil in the square has 33 mm. Hence in dry weather MORECS 2 reaches larger SMD values.

Actual Evaporation

In Fig. E16 we see that MORECS 2 has higher AE on many occasions as a result of the greater AWC in this case. The few times when MORECS 1 has higher AE are related to wetting events when rain falls onto dry soil. This rain is stored partly in the freely available water reservoir and part in the other reservoir. However, more rain is stored in the freely available reservoir in MORECS 2 because it is larger. As the deficit increases again after the rain MORECS 2 runs out of water faster than MORECS 1 and so there are usually one or two days when MORECS 1 AE is greater.

Excess Rainfall

A comparison of Figs E17 and E18 shows that MORECS 2 has fewer days with excess rain, mainly because of the higher SMDs which are reached in version 2. Over the 5-year period there is 107 mm more excess rain in MORECS 1 (1257 compared to 1150 mm).

Upland

Potential Evapotranspiration

In Figs E19 and E20 is plotted a comparison of the PE for upland in the winter (October to March) and summer (May to September). In MORECS 2 the canopy resistances have been changed from the version 1 values to increase the agreement with observations. As a result of this MORECS 2 has less evapotranspiration in winter and more in summer. This is indicated by the slopes of the two graphs (0.9614 in winter and 1.0794 in summer).

Soil Moisture Deficit

The SMD results in Fig. E21 show the effect of the higher AWC for the upland land use in MORECS 2.

Actual Evapotranspiration

The greater AWC in MORECS 2 causes higher AE, especially in spring and summer when the lower canopy resistance also contributes. There are also occasions when the MORECS 1 AE is greater than version 2 (negative values on the graph in Fig. E22). These correspond to occasions when rain falls onto dry soil. MORECS 2 evaporates this water at a higher rate because of the lower canopy resistance and so the maximum SMD is reached faster than in MORECS 1.

Excess Rainfall

A comparison of Figs E23 and E24 shows a reduced number of occasions of excess rain for MORECS 2, mainly as a result of delayed return to capacity. For the 5-year period a total of 913.8 mm was calculated for MORECS 1 and 838.5 mm for version 2 which is a difference of 75.3 mm.

Oil-seed rape

The oil-seed rape crop model in MORECS 2 is based upon a thermal time concept of growth and so there is a basic difference between the model for this crop and the others. A comparison is made between the results for a season with a cool growing season (1986–1987) and another with an exceptionally warm season (1989–1990). The crop growth is estimated from the thermal time above a base of 4 °C from the assumed sowing date of 1 September. Fig. E25 shows the thermal times above base 4 °C for the two growing seasons. The cooler year in 1986–87 is shown to accumulate thermal time at a slower rate and in winter and early spring there was very little accumulation until day 105.

The slower temperature accumulation in the cooler year caused the development of leaf area and crop height to be slower as well. The effect of this on the PE is shown in Fig. E26. The much lower PE in the cool season up to about day 85 is clear which is due to low leaf area and shorter crops as well as lower temperatures. The spring delay is also shown in Fig. E27 which is a plot of the SMD in the two years.

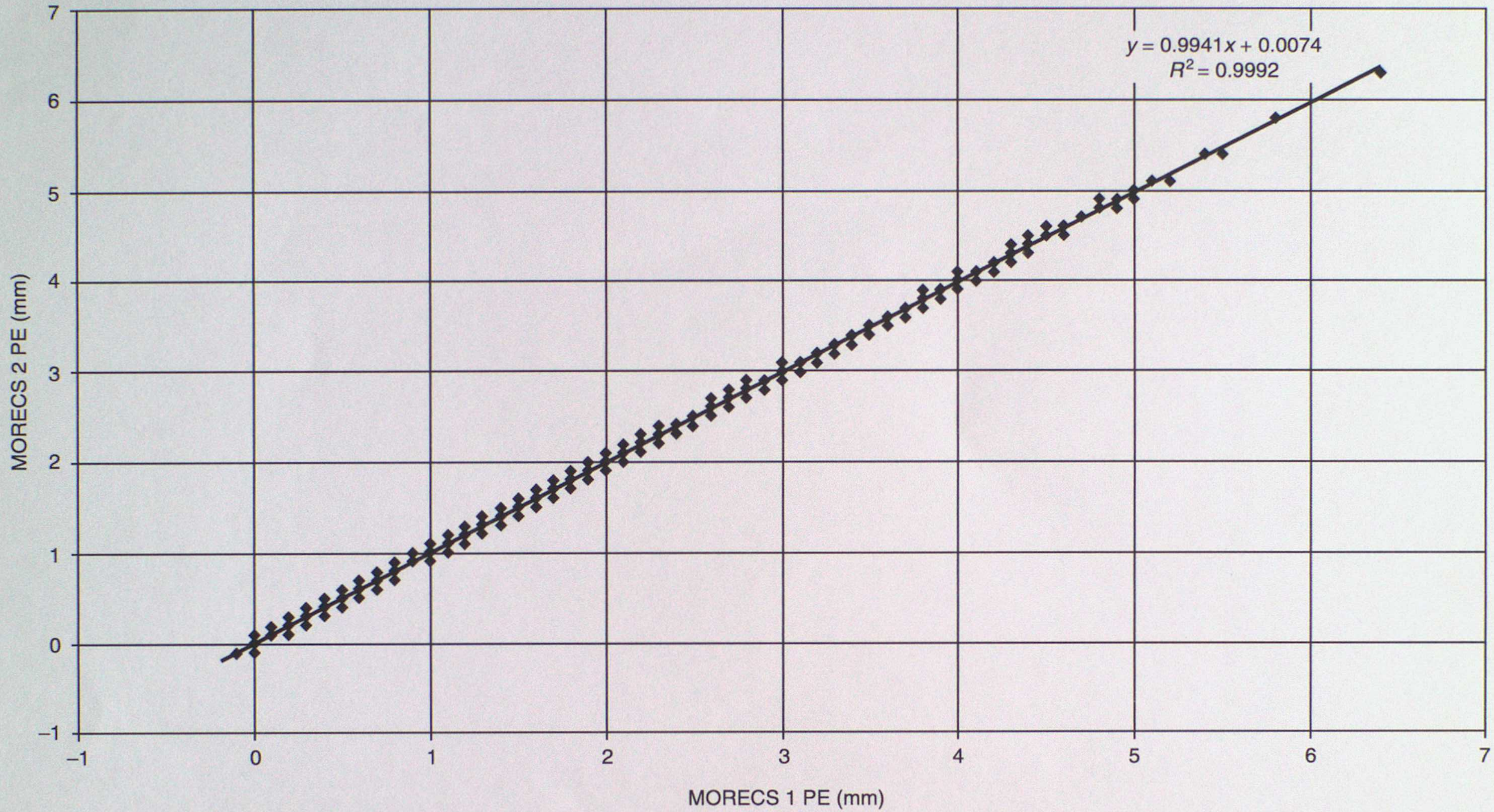

Figure E1.
MORECS 1 and 2 daily values of PE at Newport for grass from 1987 to 1991.

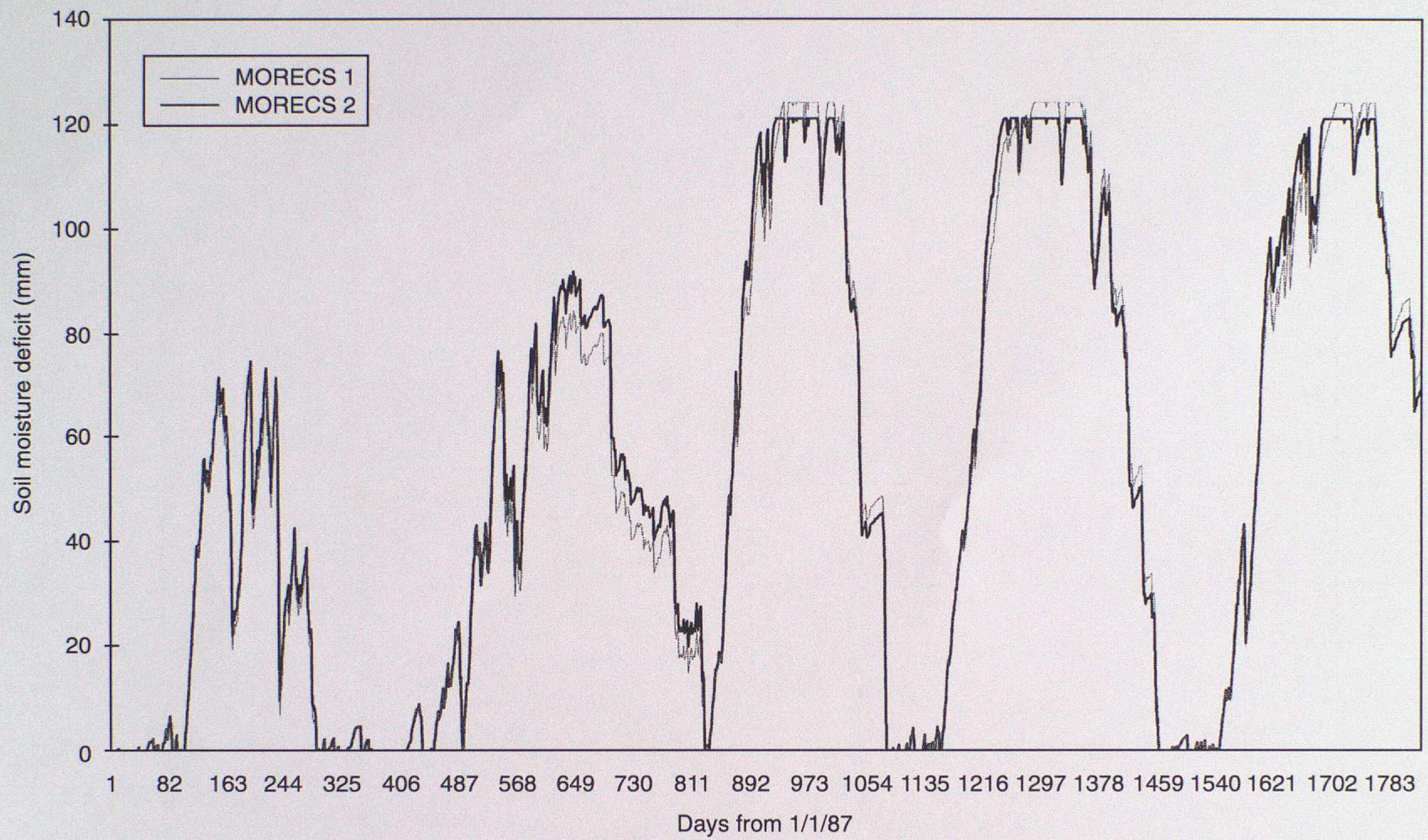

Figure E2.
Soil moisture deficit at Newport for MORECS 1 (grass, medium soil) and MORECS 2 (grass, median soil) for 1987 to 1991.

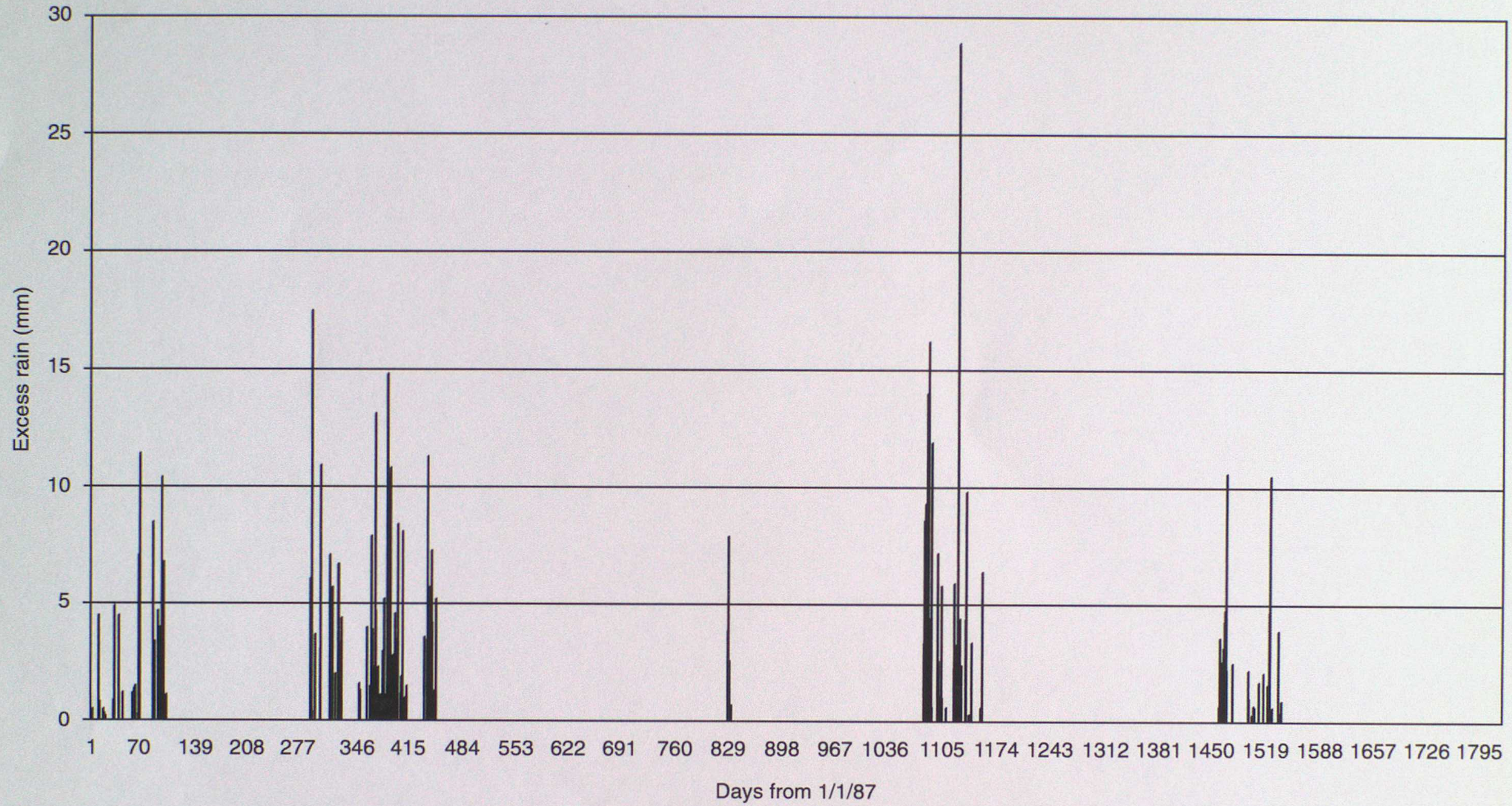

Figure E3.
Daily values of excess rain at Newport from 1987 to 1991 for grass on medium soil (MORECS 1).

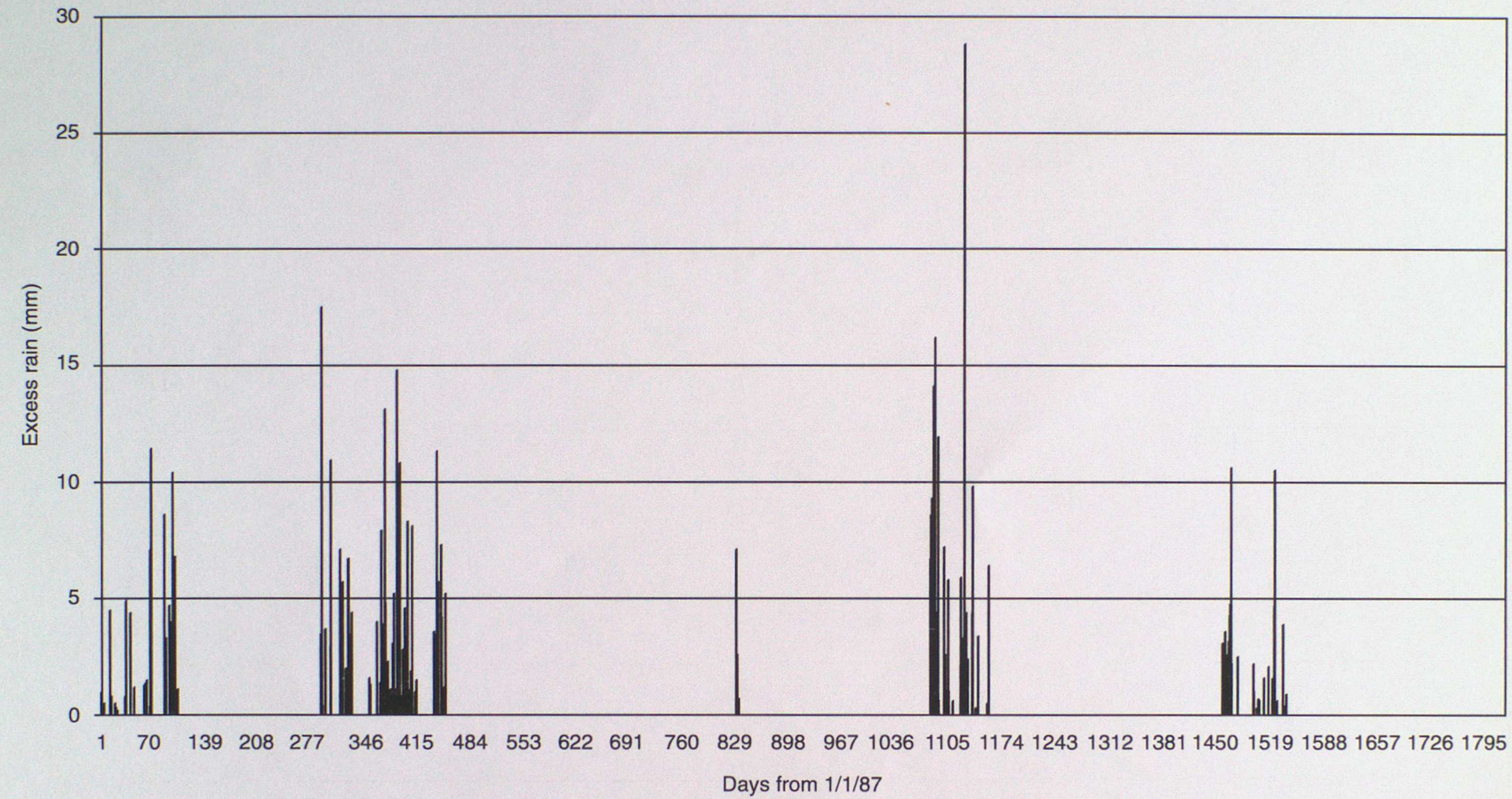

Figure E4.
Daily values of excess rain at Newport from 1987 to 1991 for grass on median soil (MORECS 2).

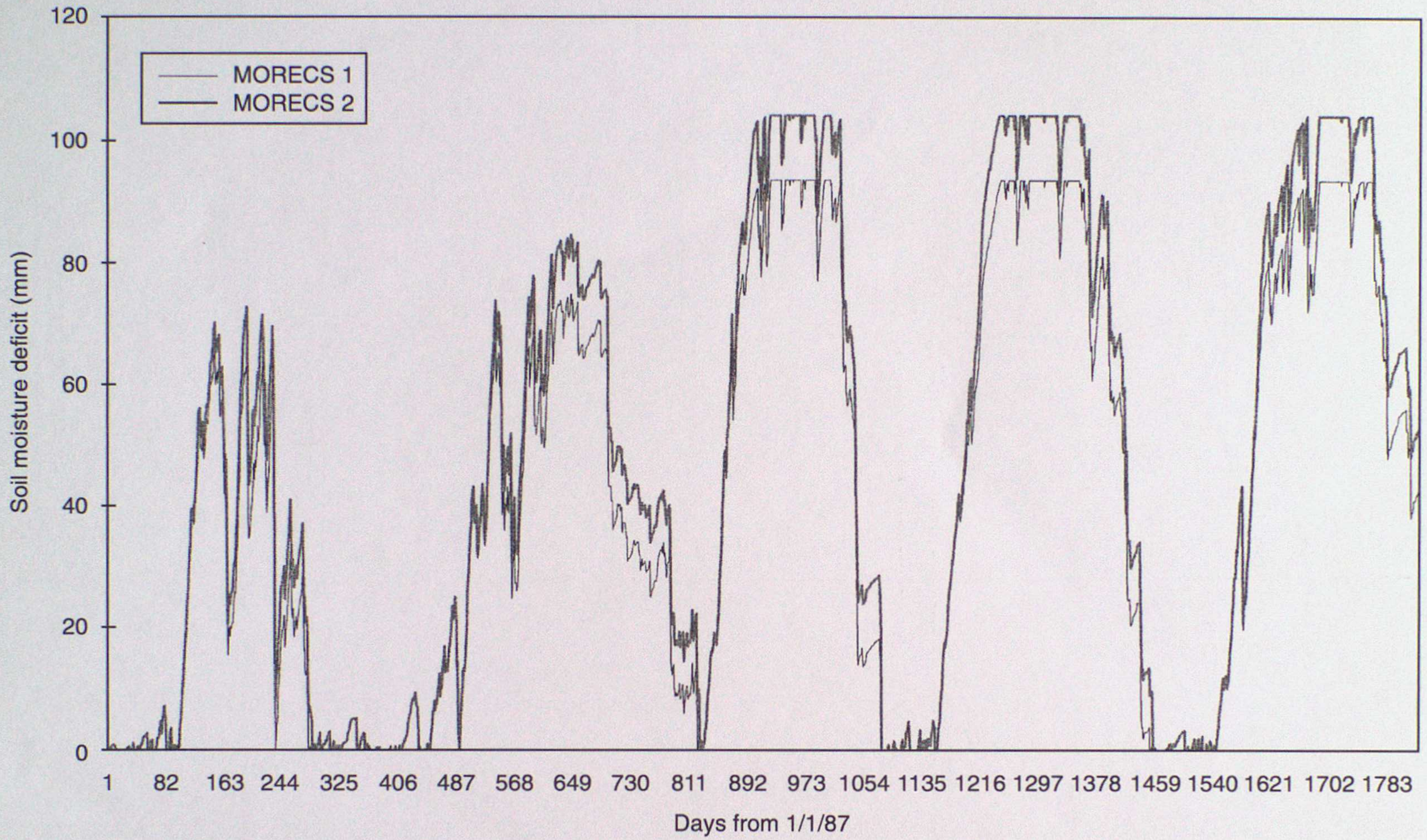

Figure E5.

Soil moisture deficit at Newport for MORECS 1 (grass, low AWC soil) and MORECS 2 (grass, 10 percentile soil) for 1987 to 1991.

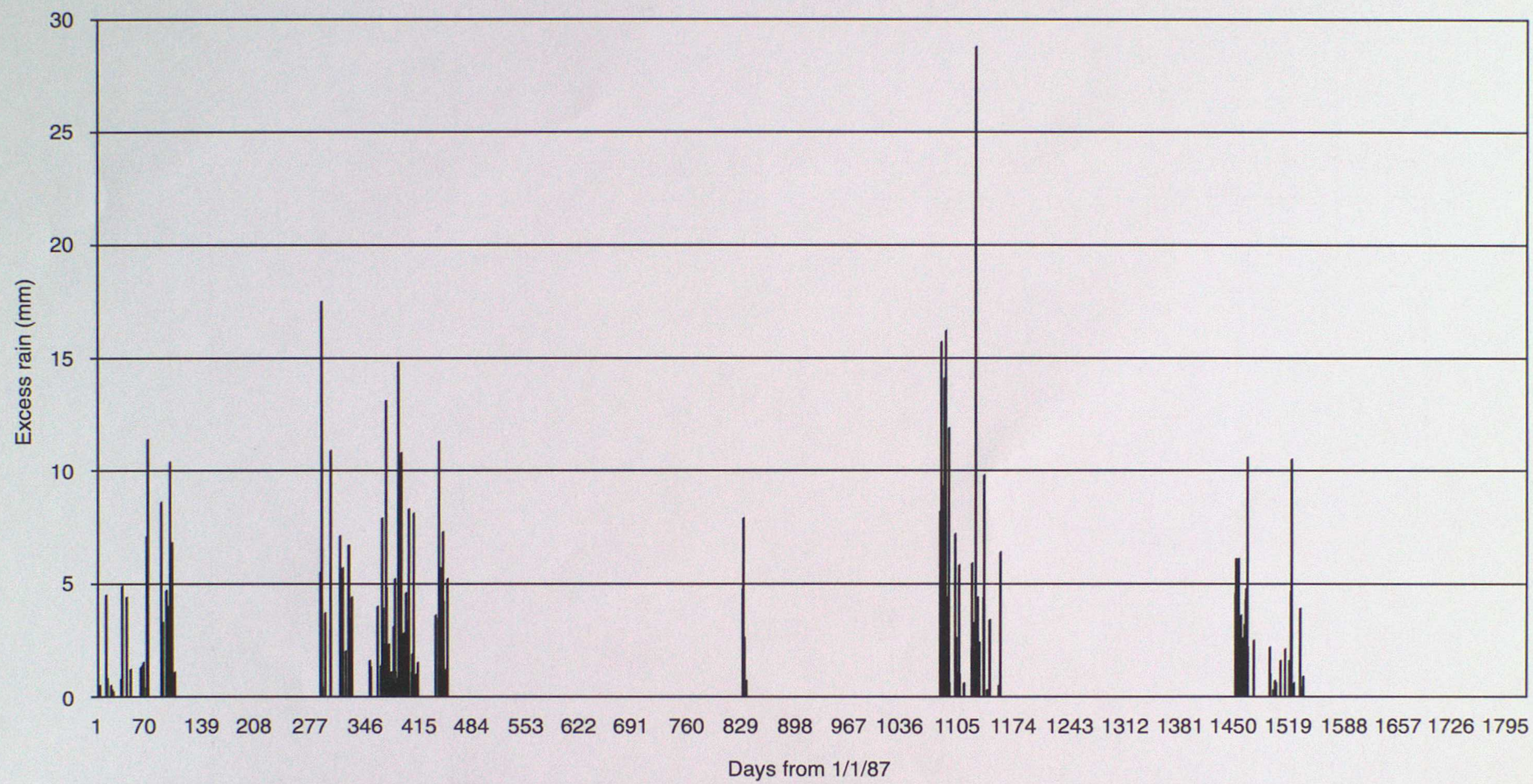

Figure E6.
Daily values of excess rain at Newport from 1987 to 1991 for grass on the 10 percentile soil (MORECS 2).

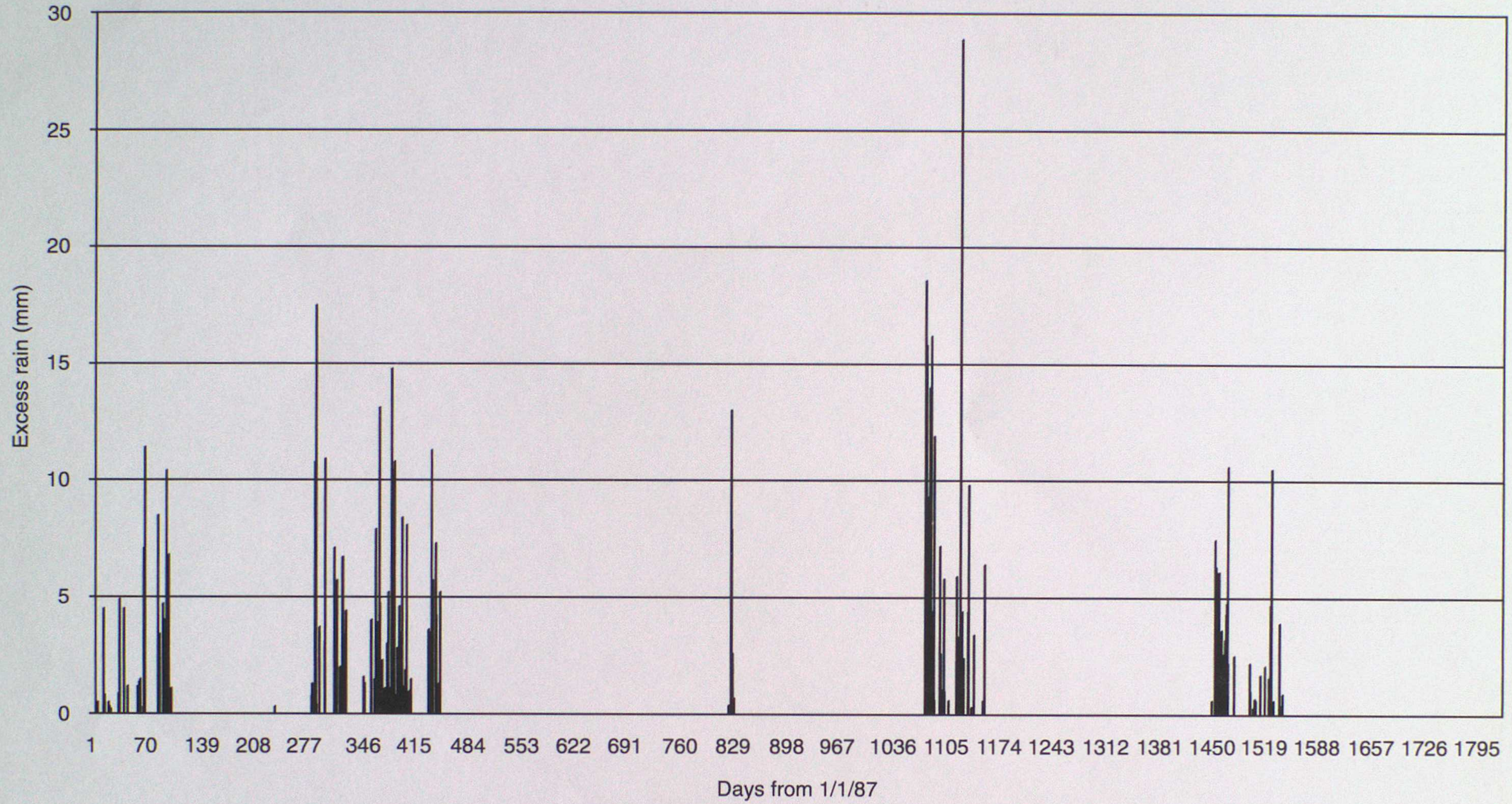

Figure E7.
Daily values of excess rain at Newport from 1987 to 1991 for grass on low AWC soil (MORECS 1).

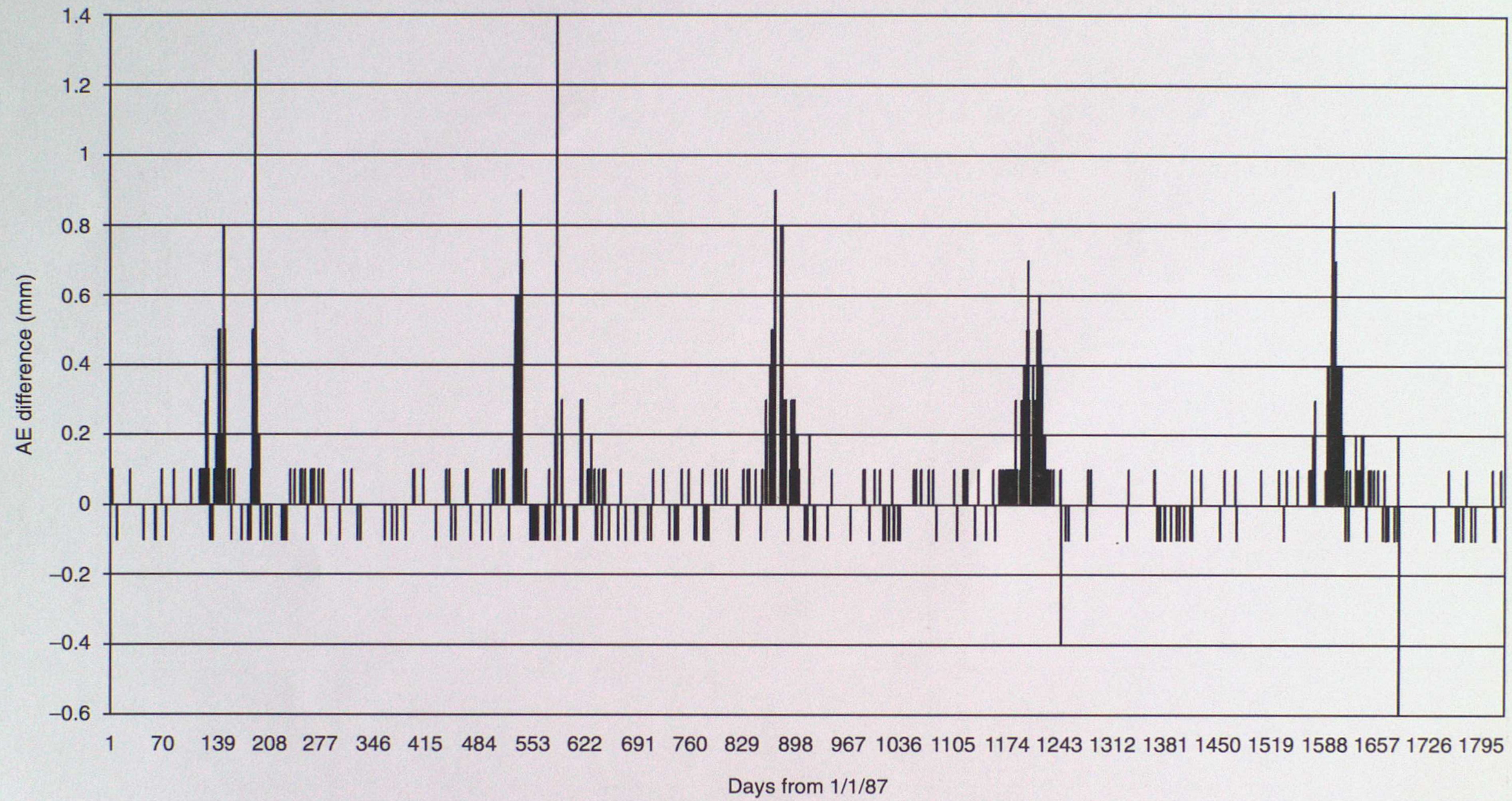

Figure E8.
The values of AE (MORECS 2, 10 percentile soil) minus AE (MORECS 1, low AWC soil) for grass at Newport 1987 to 1991.

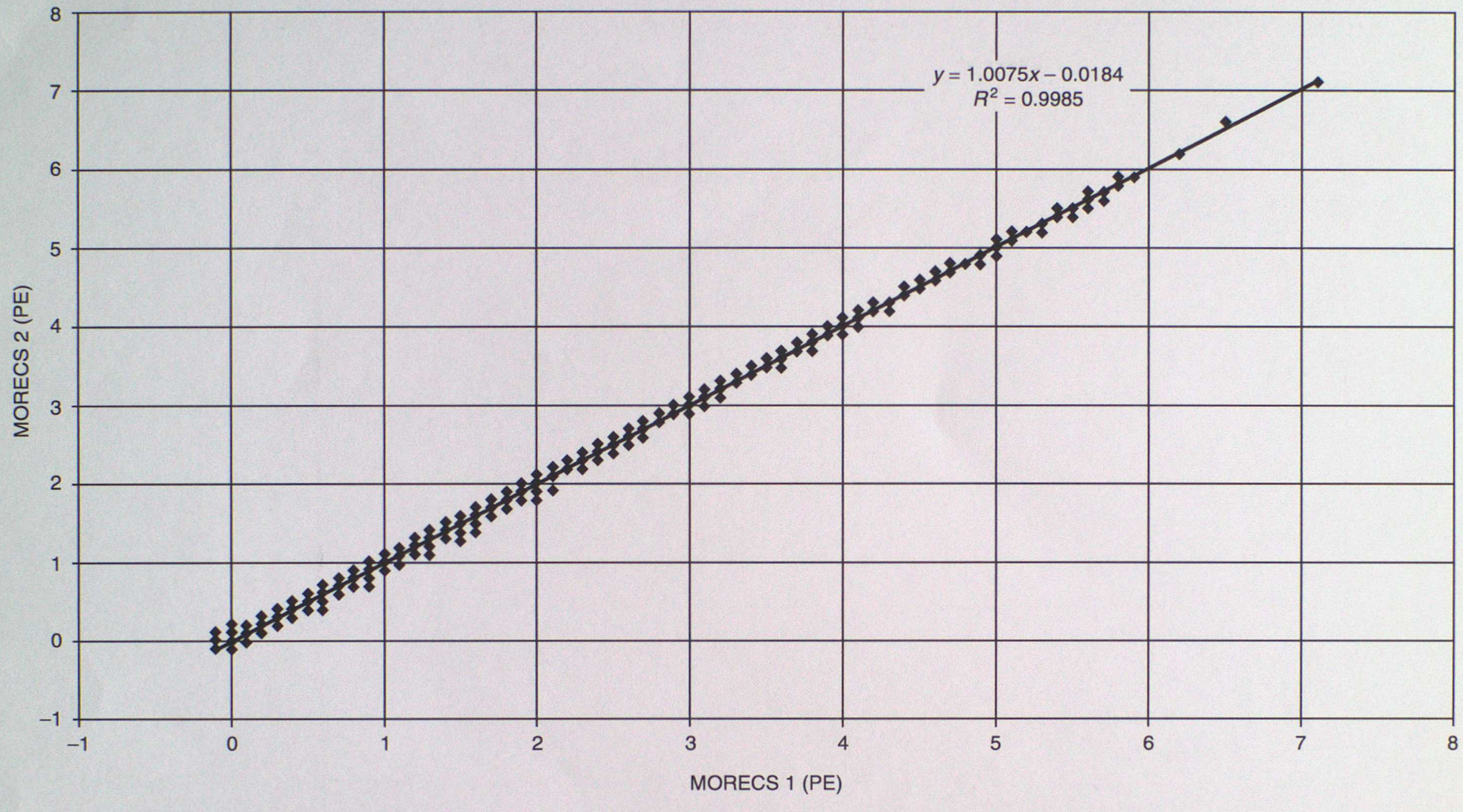

Figure E9.
MORECS 1 and 2 PE for winter wheat at Newport from 1987 to 1991.

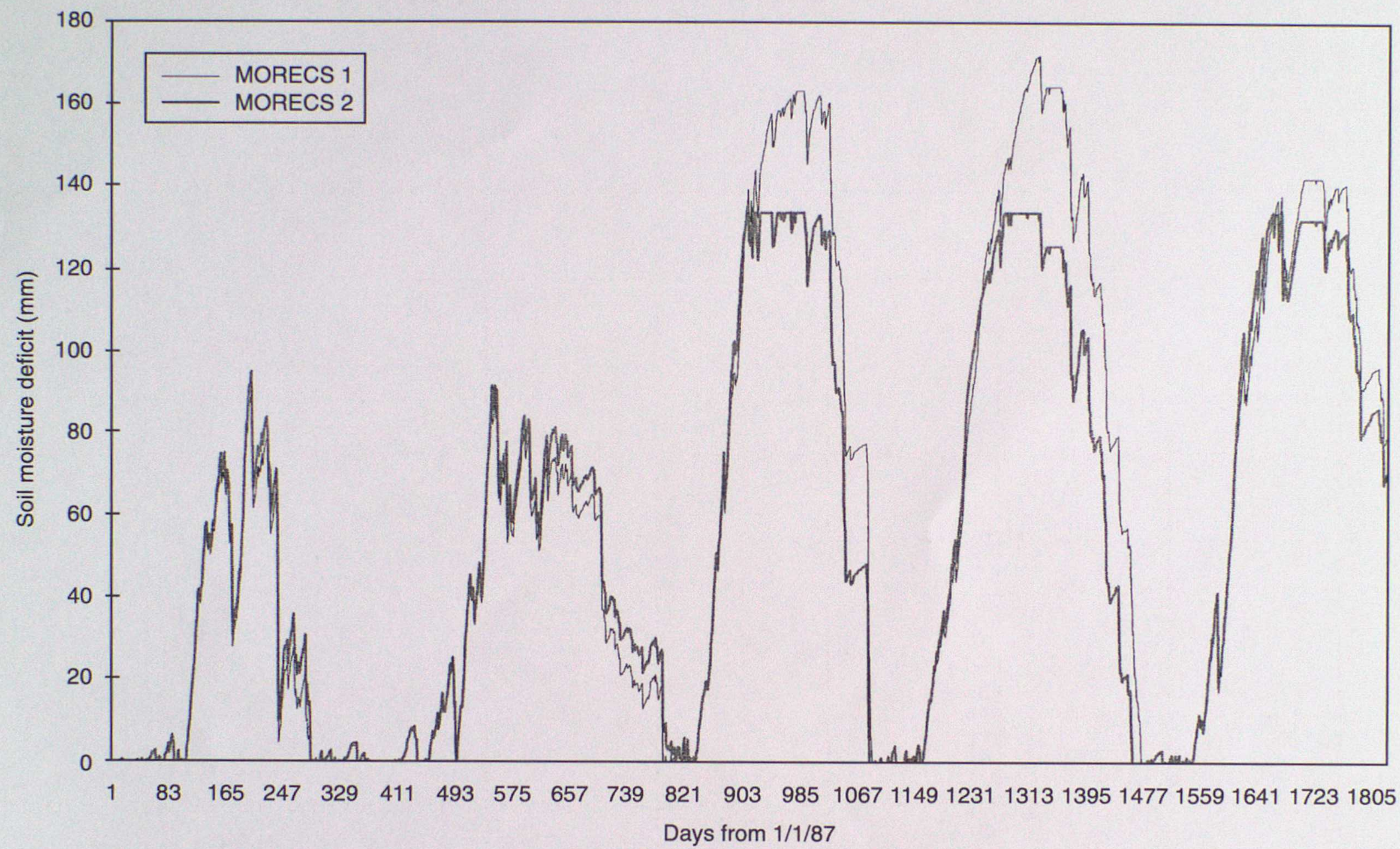

Figure E10.
Soil moisture deficit at Newport for MORECS 1 (winter wheat, high AWC soil) and MORECS 2 (winter wheat, 90 percentile soil) from 1987 to 1991.

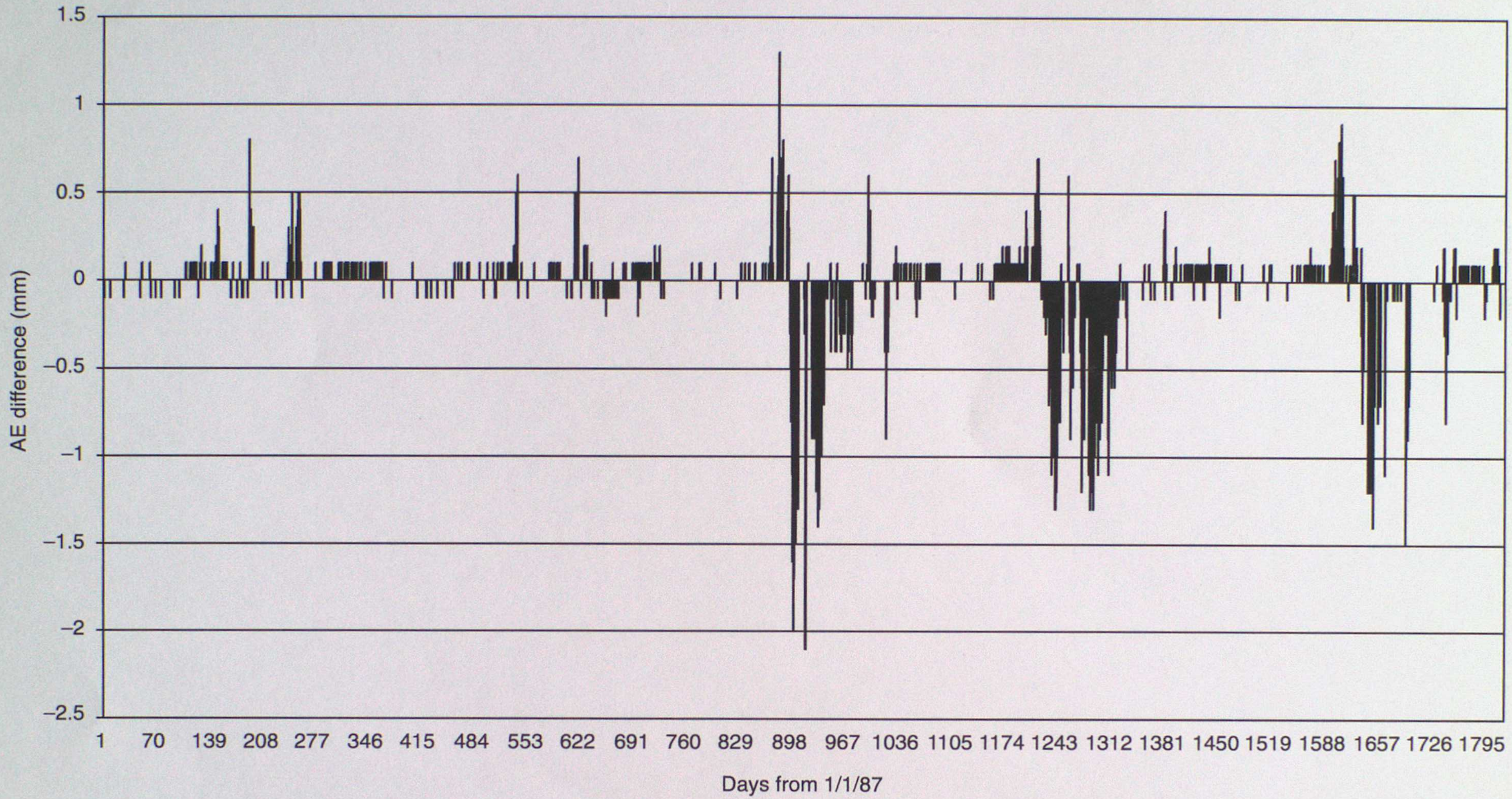

Figure E11.
The values of AE (MORECS 2, 90 percentile soil) minus AE (MORECS 1, high AWC soil) for winter wheat at Newport from 1987 to 1991.

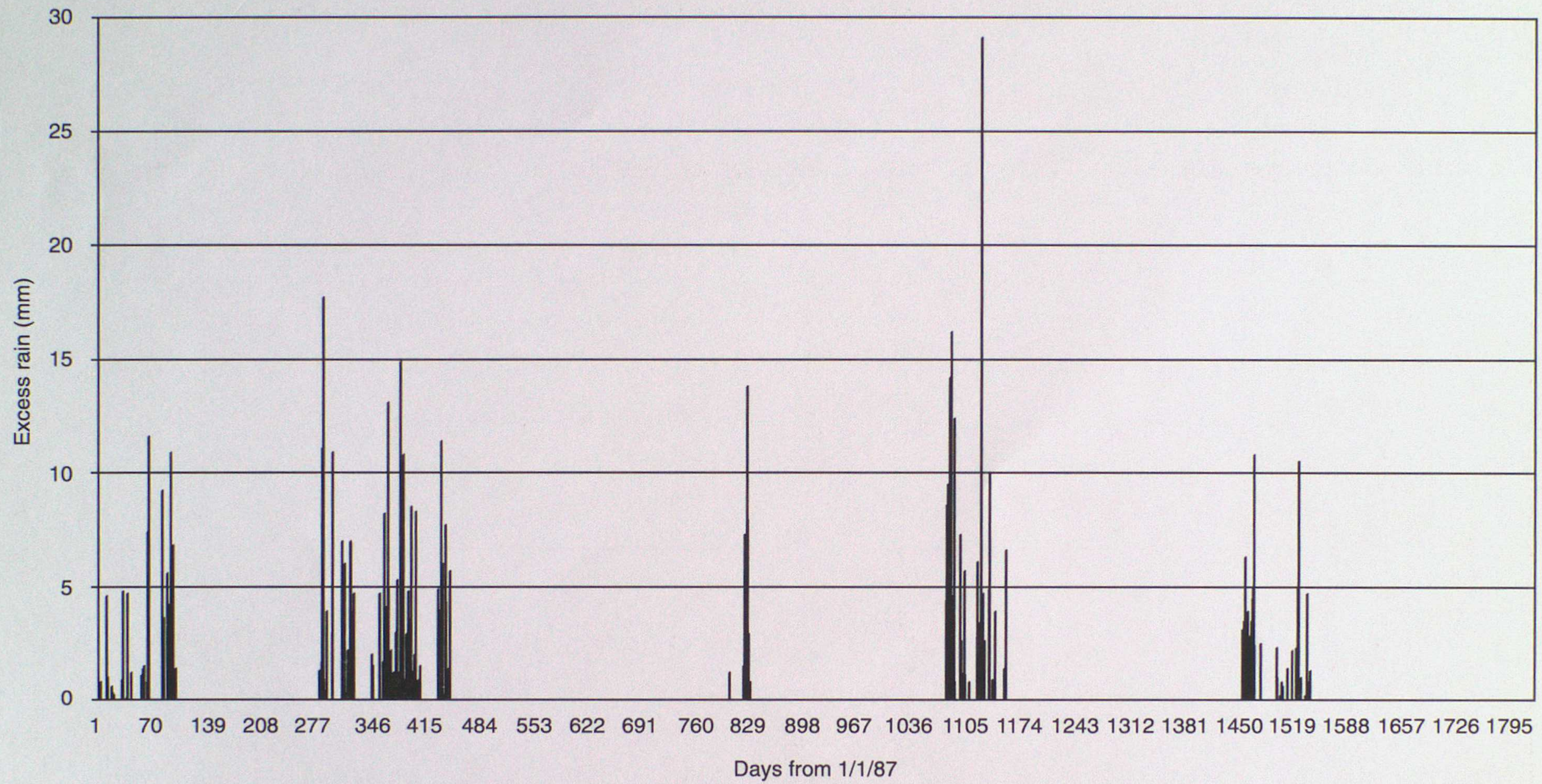

Figure E12.
Daily values of excess rain at Newport from 1987 to 1991 for winter wheat on the 90 percentile soil (MORECS 2).

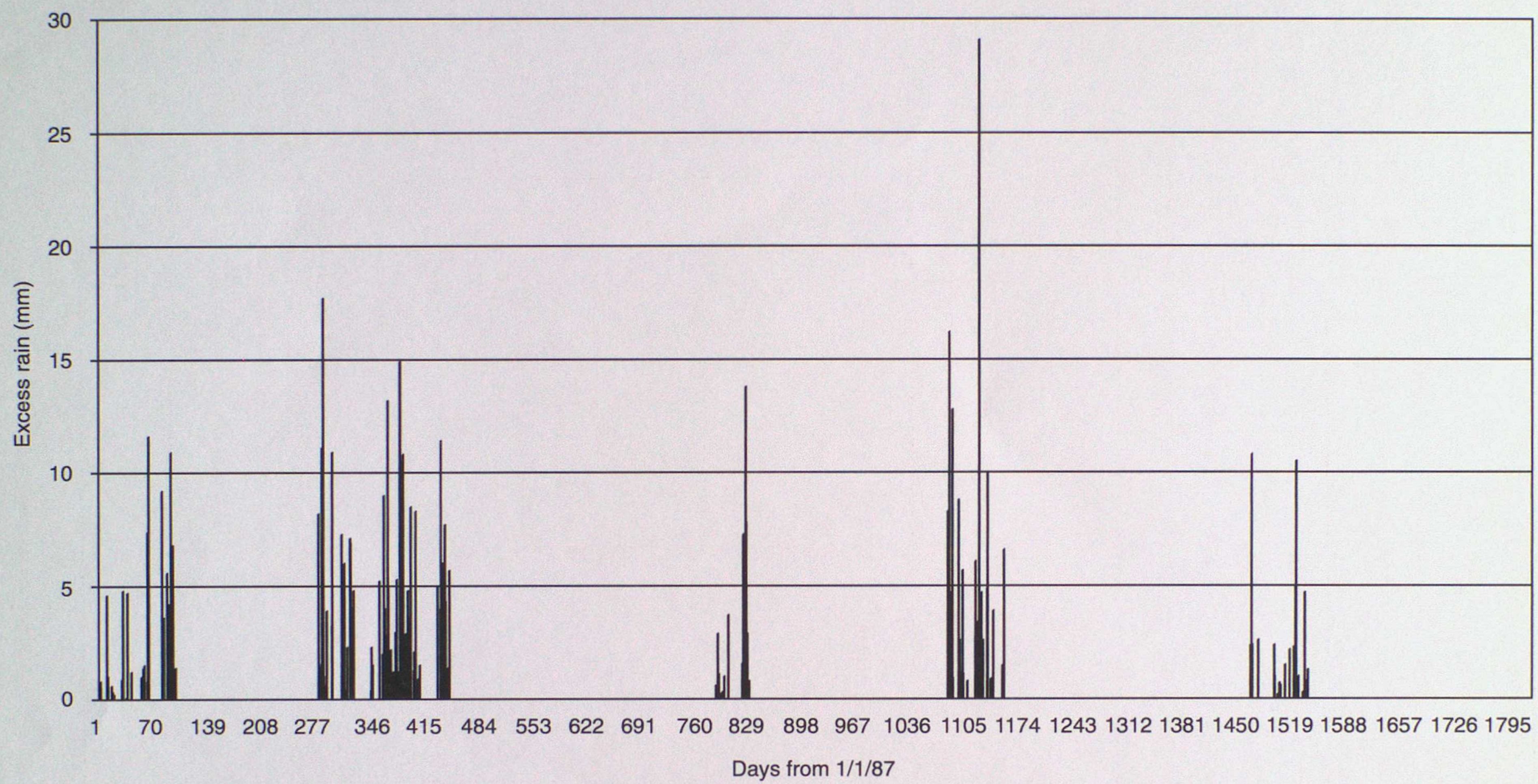

Figure E13.
Daily values of excess rain at Newport from 1987 to 1991 for winter wheat on high AWC soil (MORECS 1).

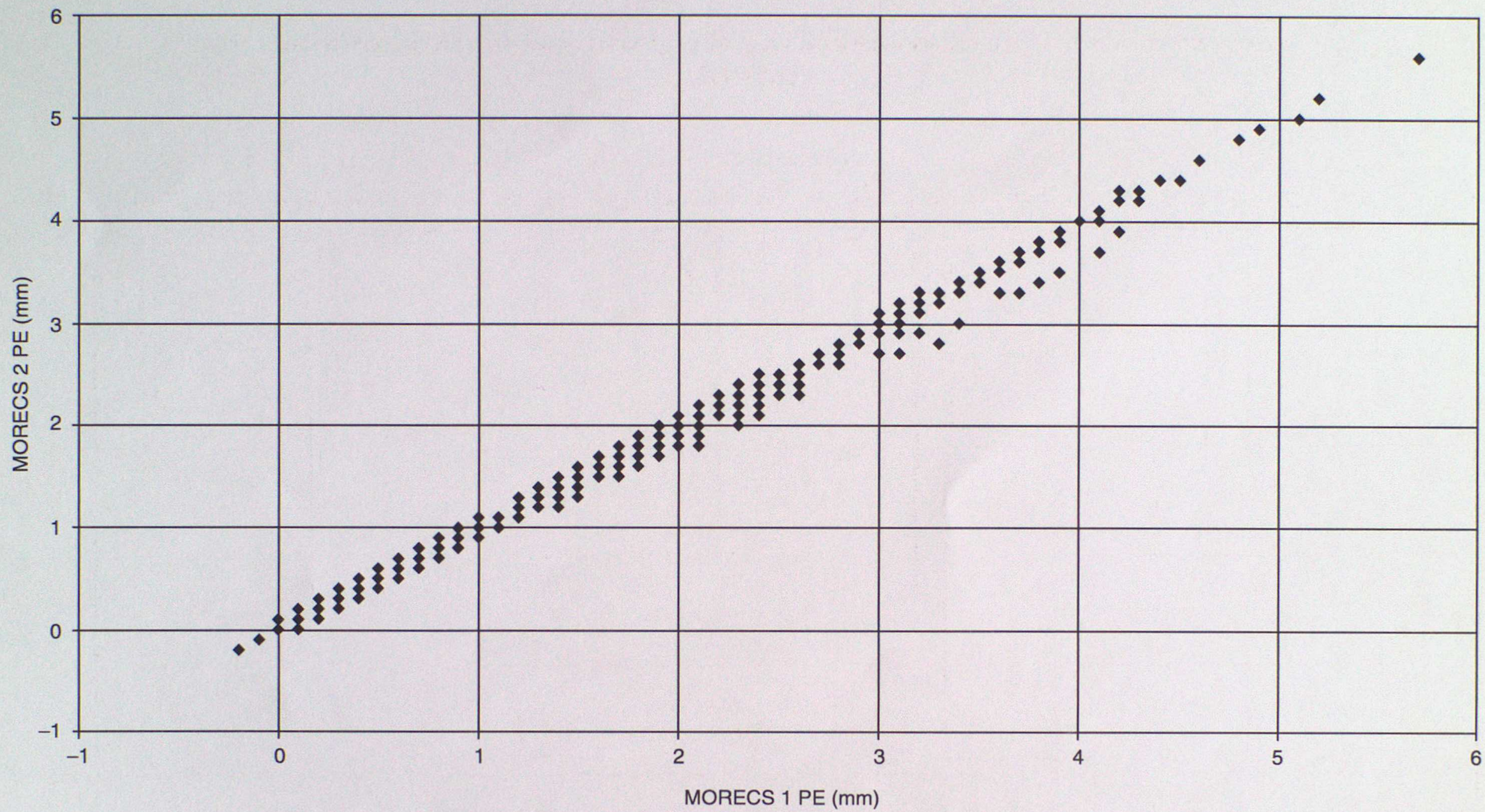

Figure E14.
MORECS 1 and 2 PE for bare soil at Newport from 1987 to 1991.

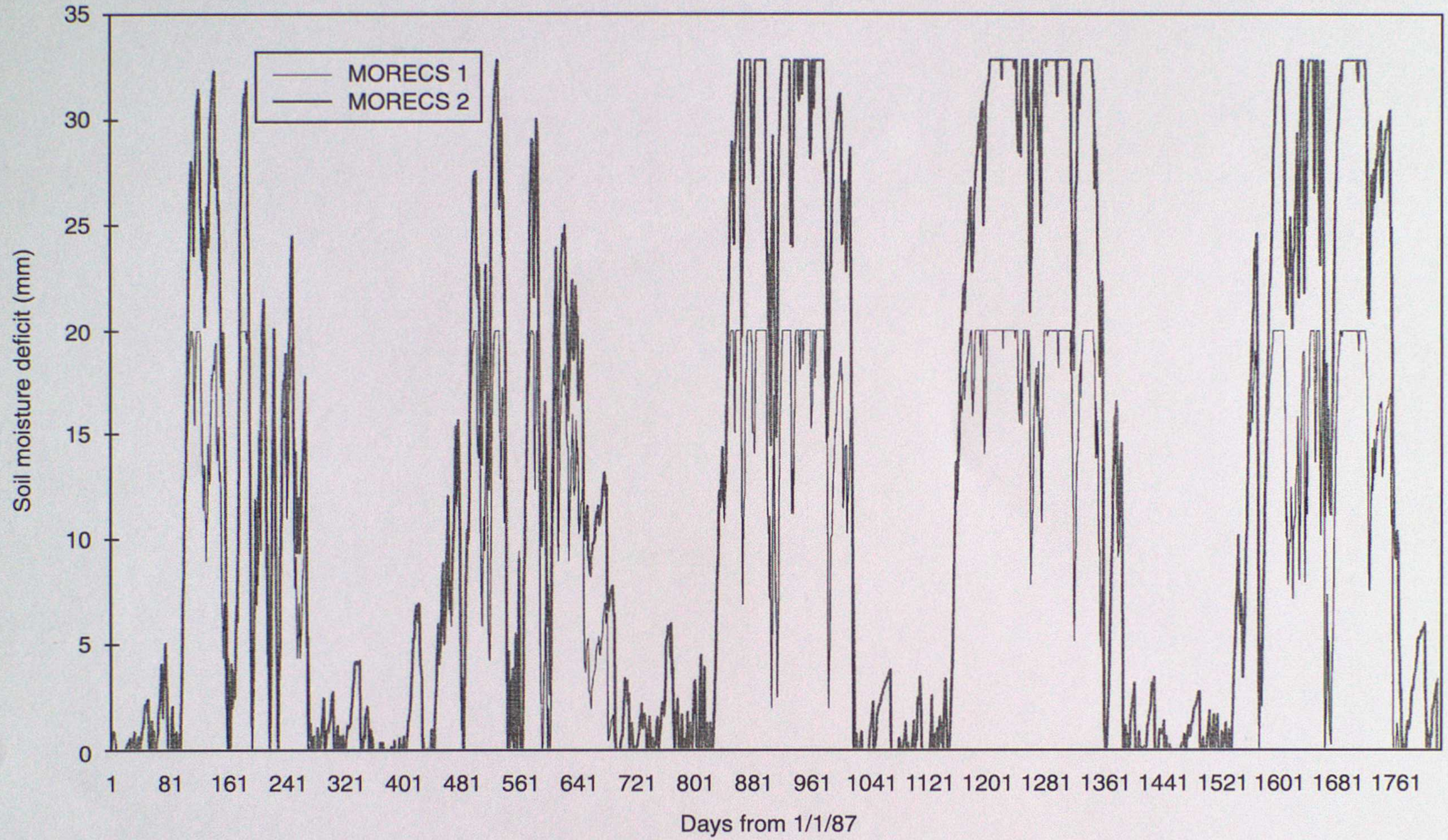

Figure E15.
Soil moisture deficit for bare soil at Newport for MORECS 1 (medium AWC soil) and MORECS 2 (median soil) for 1987 to 1991.

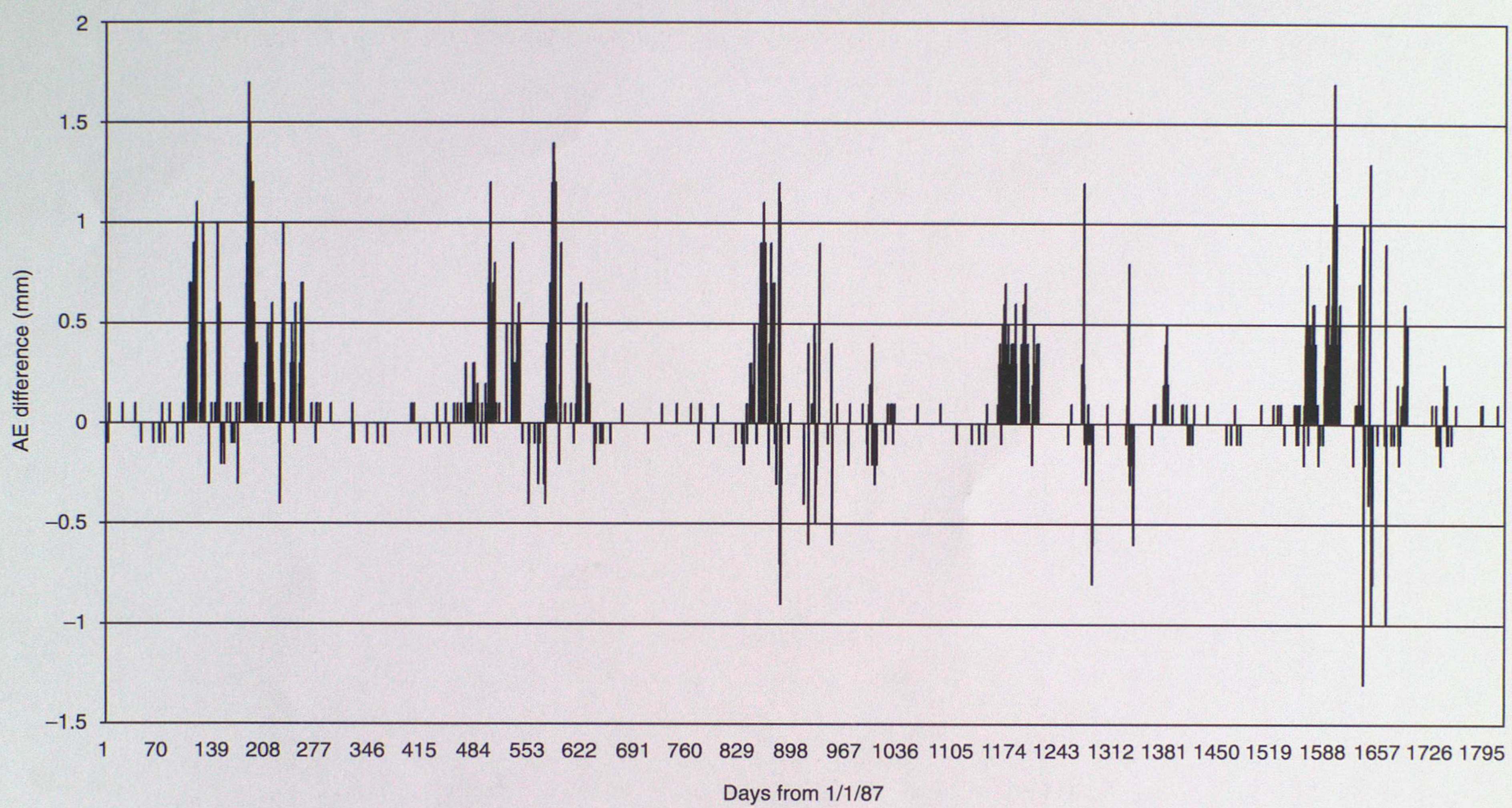

Figure E16.
The values of AE (MORECS 2, median soil) minus AE (MORECS 1, medium AWC soil) for bare soil at Newport from 1987 to 1991.

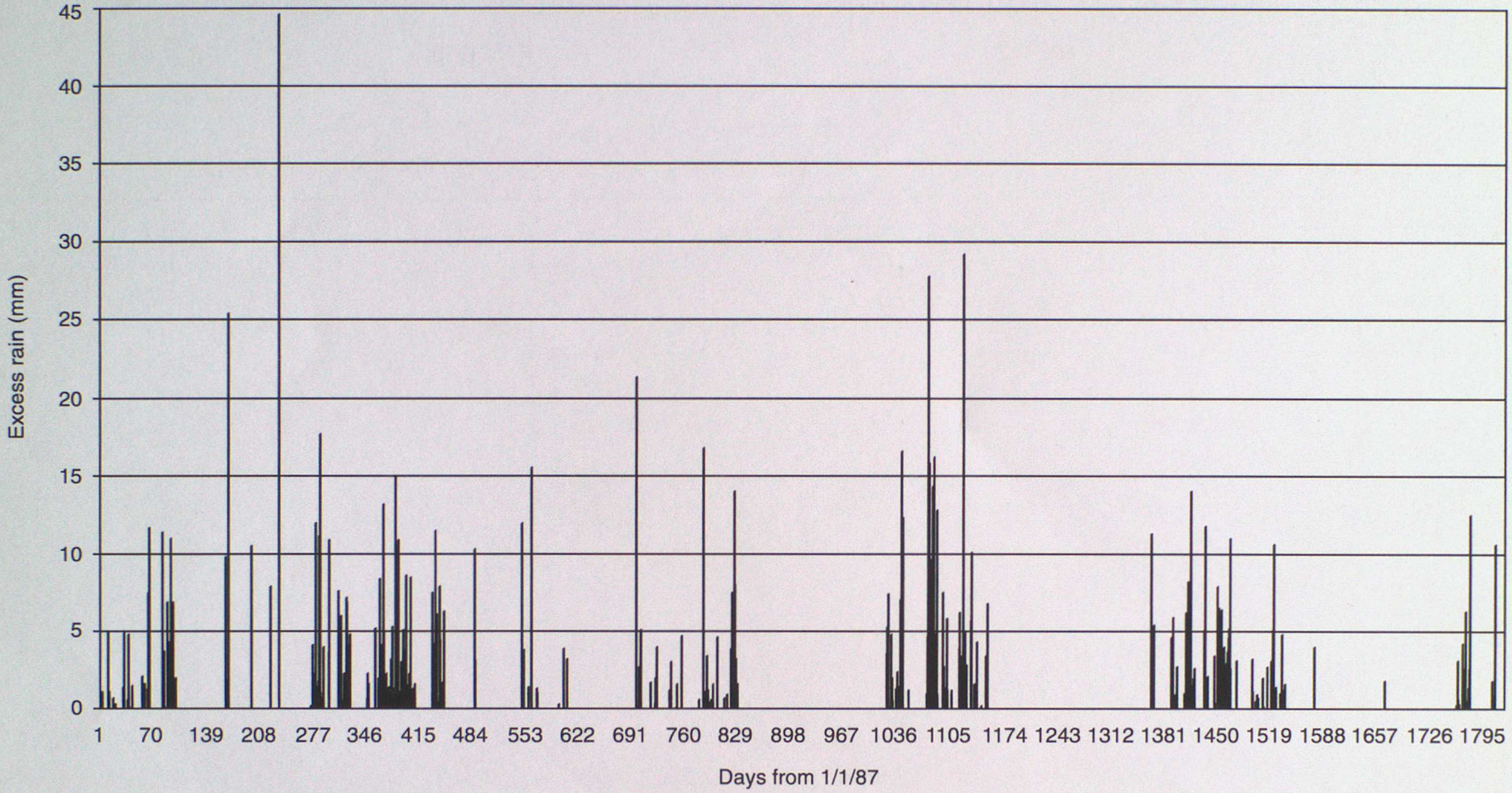

Figure E17.
Daily values of excess rain at Newport from 1987 to 1991 for medium AWC bare soil (MORECS 1).

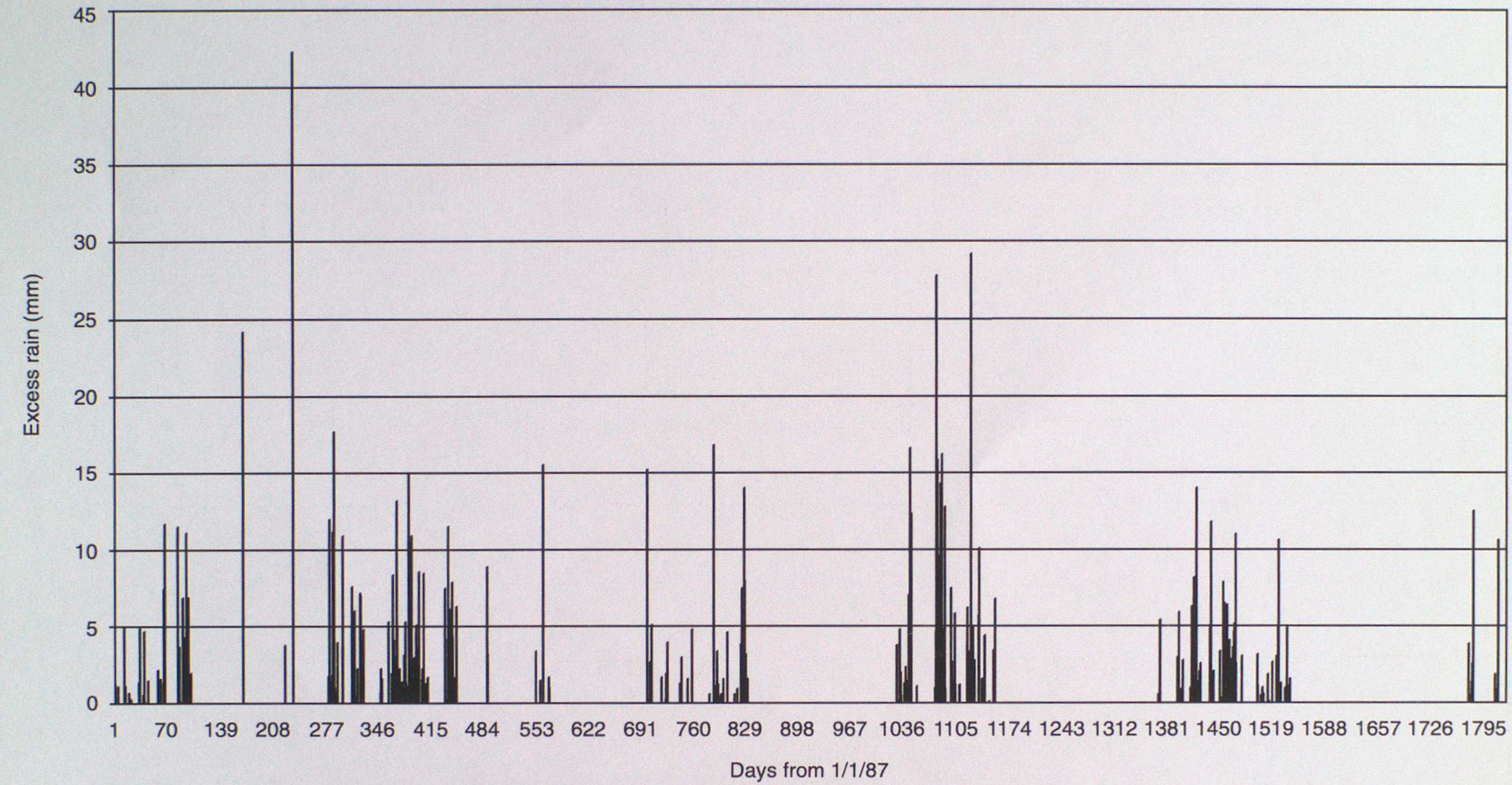

Figure E18.
Daily values of excess rain at Newport from 1987 to 1991 for median AWC bare soil (MORECS 2).

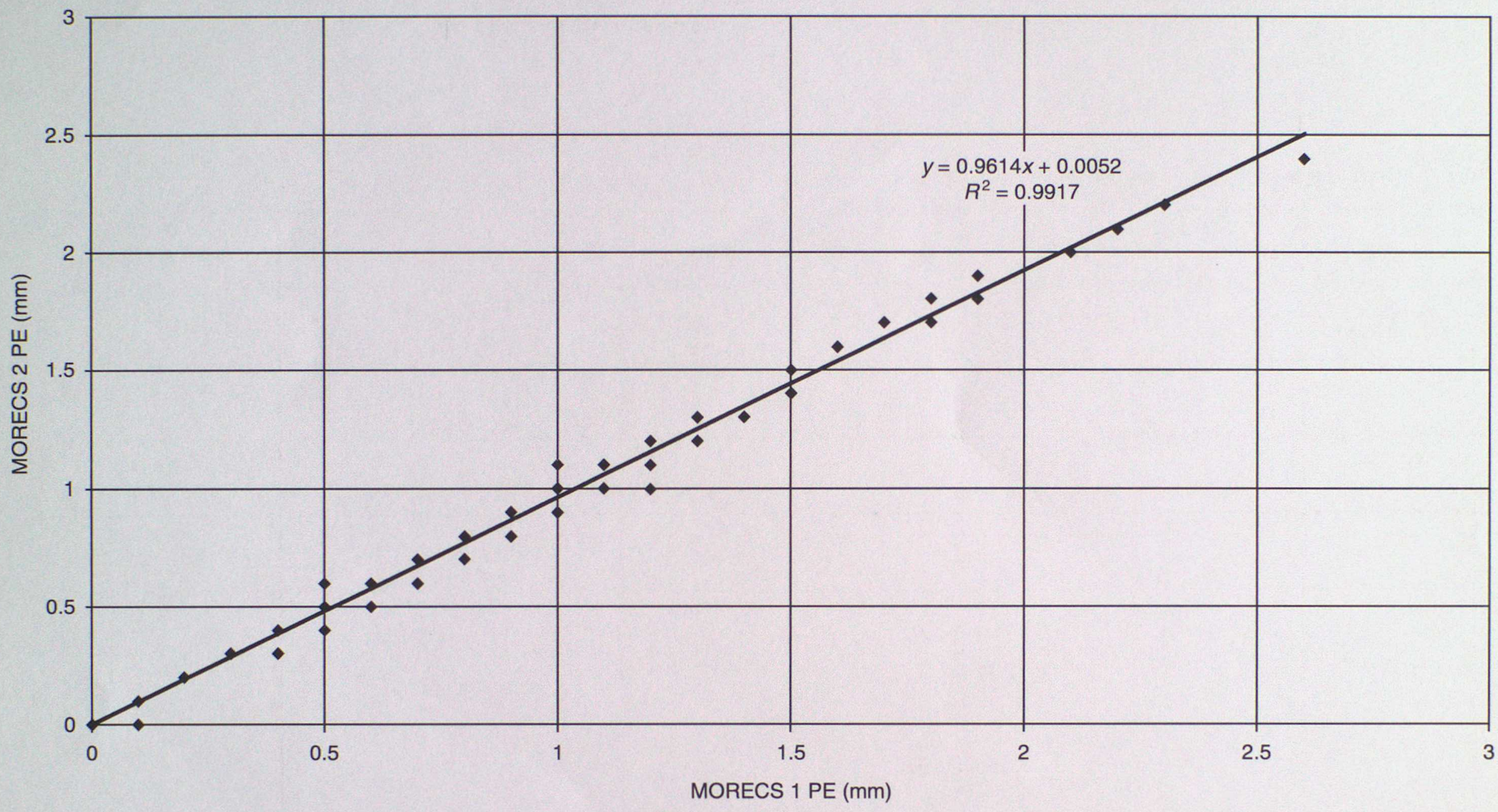

Figure E19.
MORECS 1 and 2 PE for upland at Newport from October 1987 to March 1988.

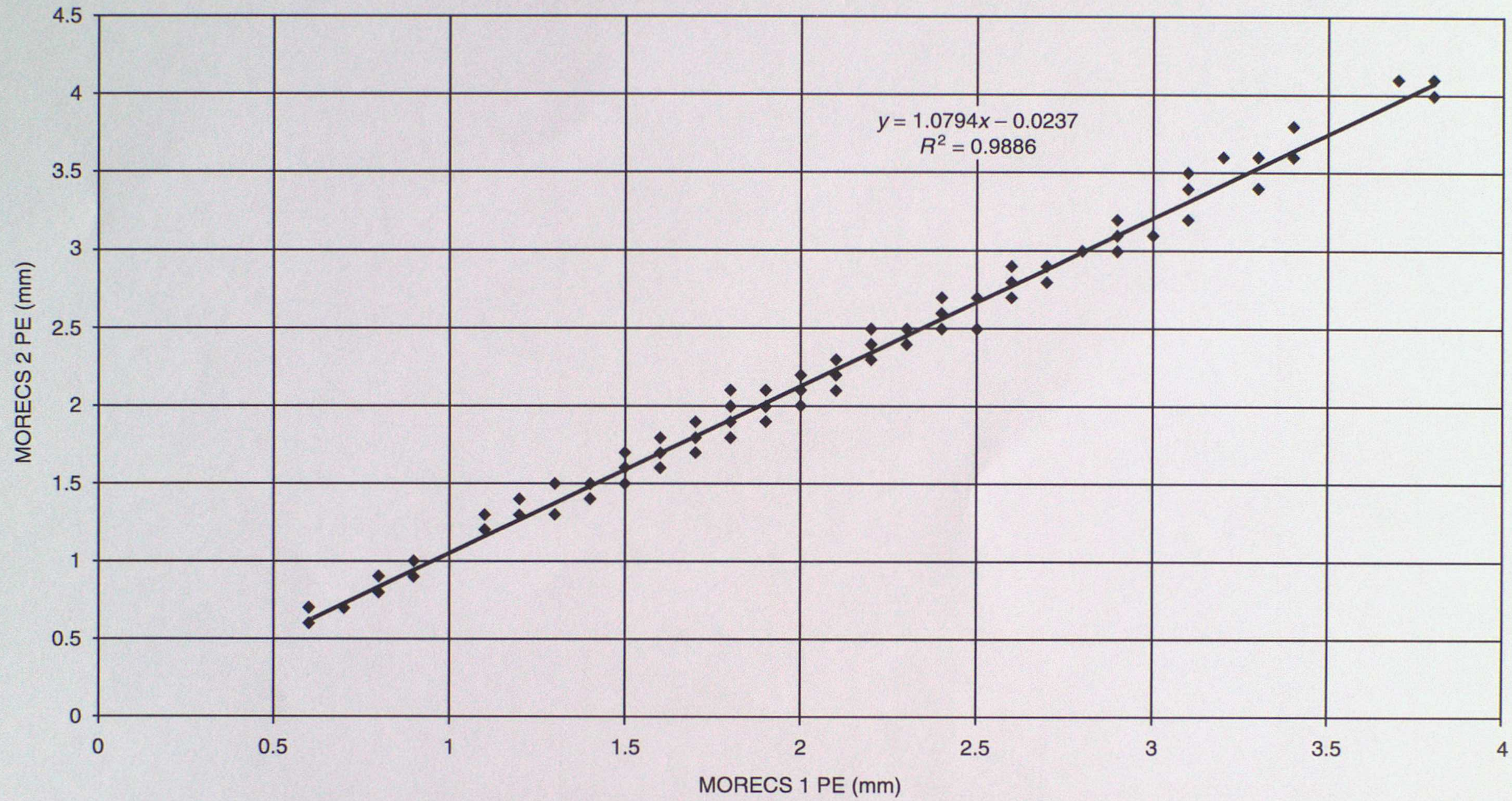

Figure E20.
MORECS 1 and 2 PE for upland at Newport from May to September 1987.

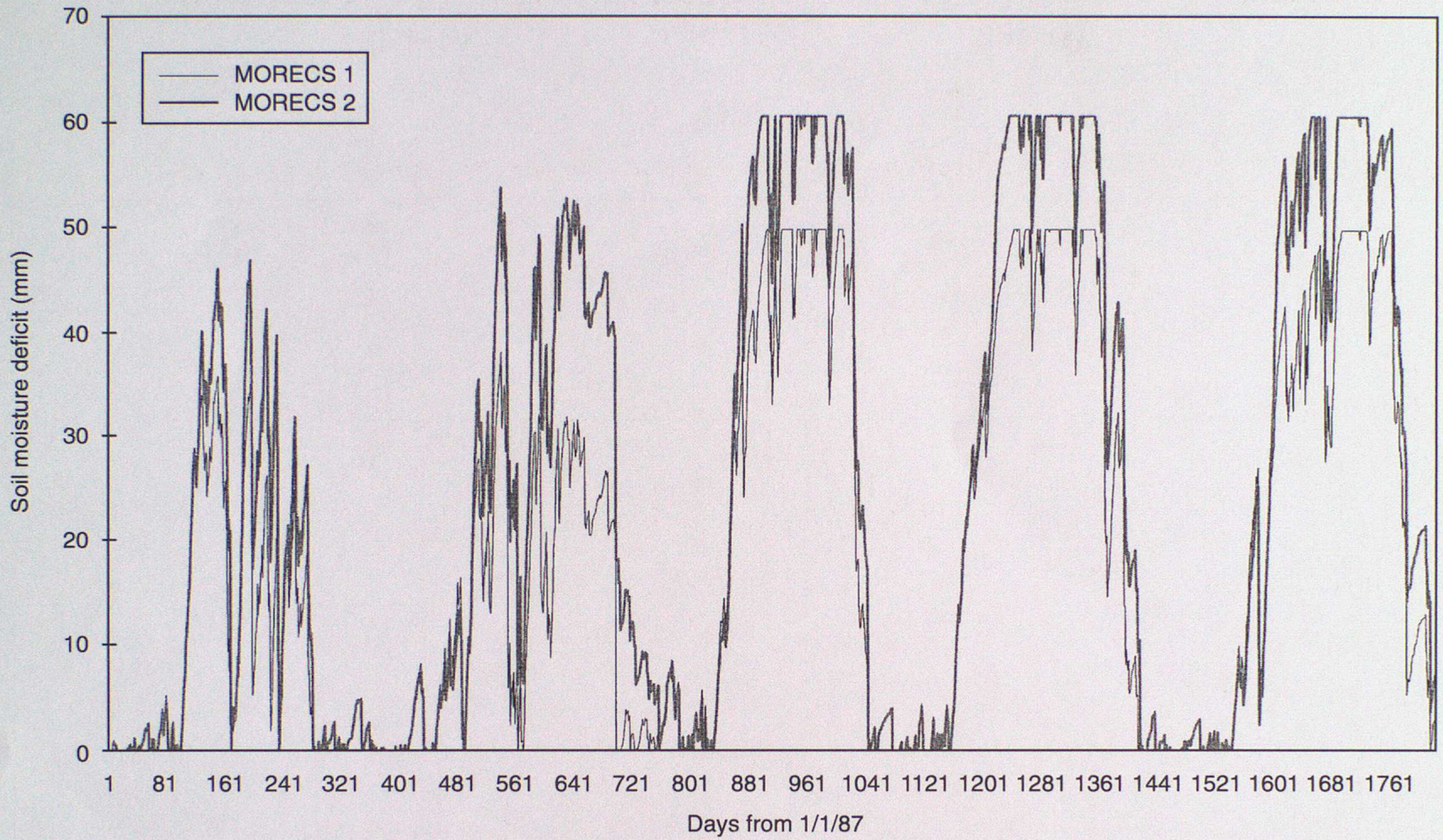

Figure E21.
Soil moisture deficit at Newport for MORECS 1 (upland, medium AWC soil) and MORECS 2 (upland, median soil).

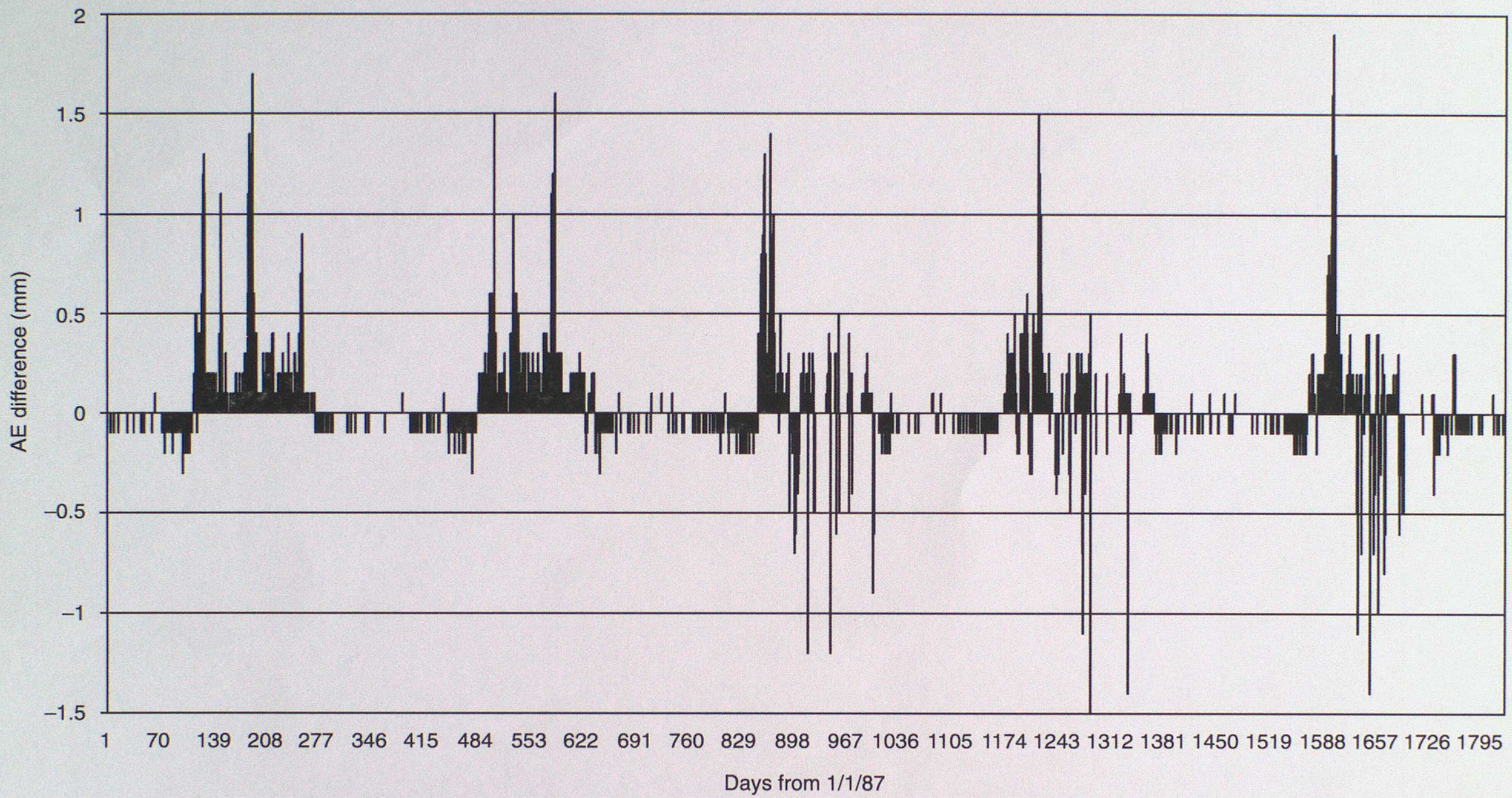

Figure E22.
The value of AE (MORECS 2, median soil) minus AE (MORECS 1, medium soil) for upland at Newport from 1987 to 1991.

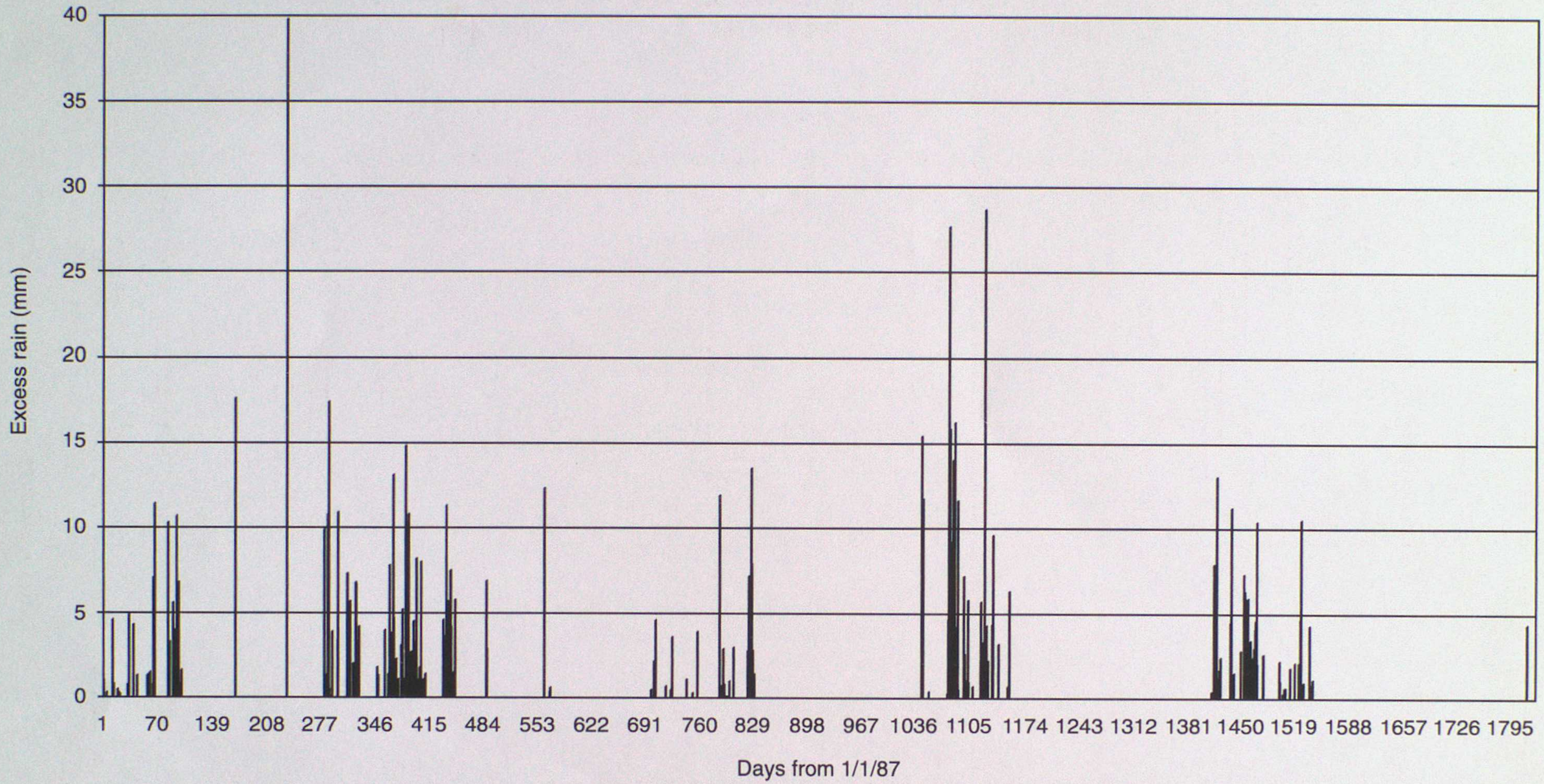

Figure E23.
Daily values of excess rain at Newport from 1987 to 1991 for upland on medium AWC soil (MORECS 1).

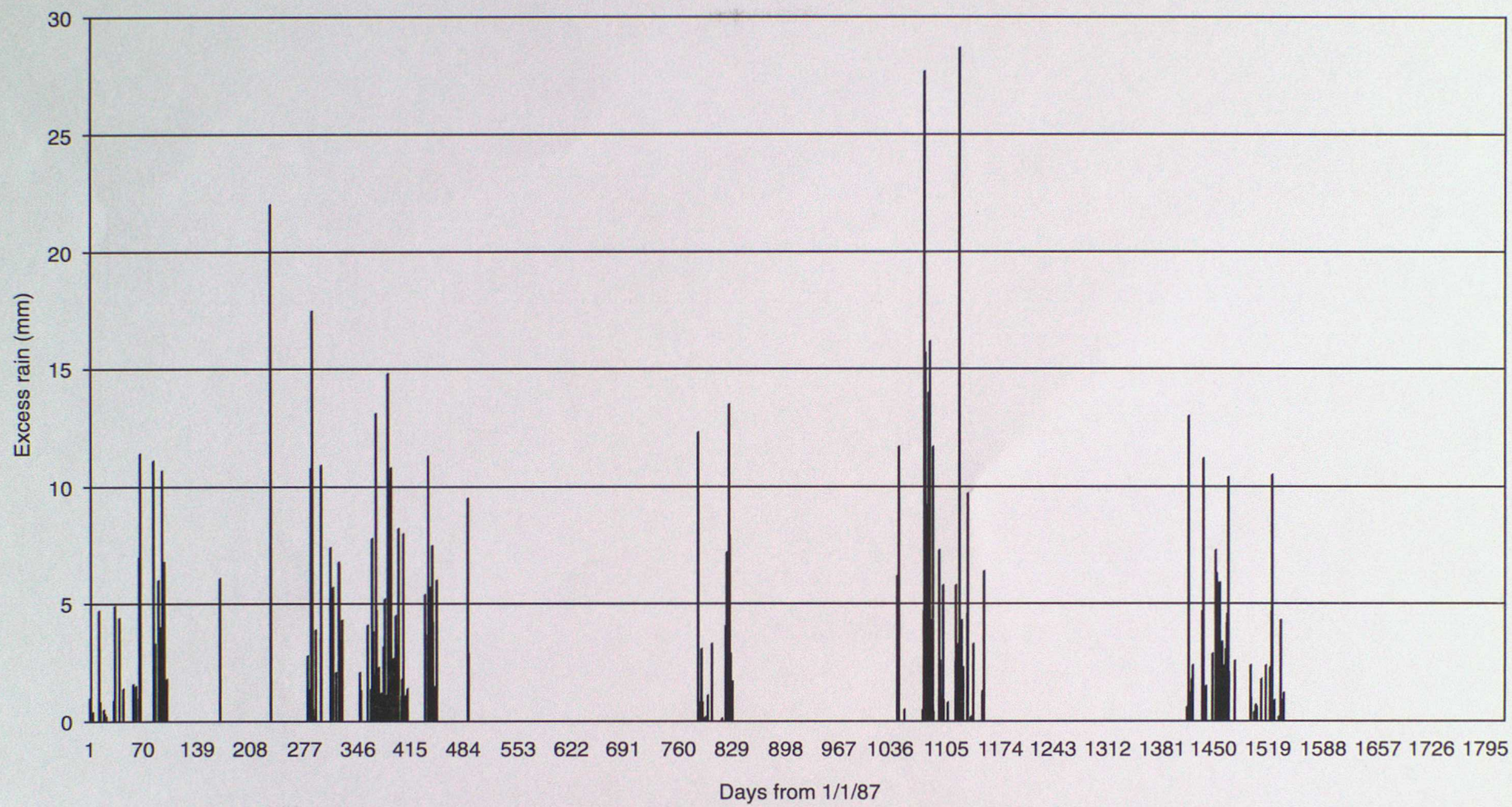

Figure E24.
Daily values of excess rain at Newport from 1987 to 1991 for upland on median AWC soil (MORECS 2).

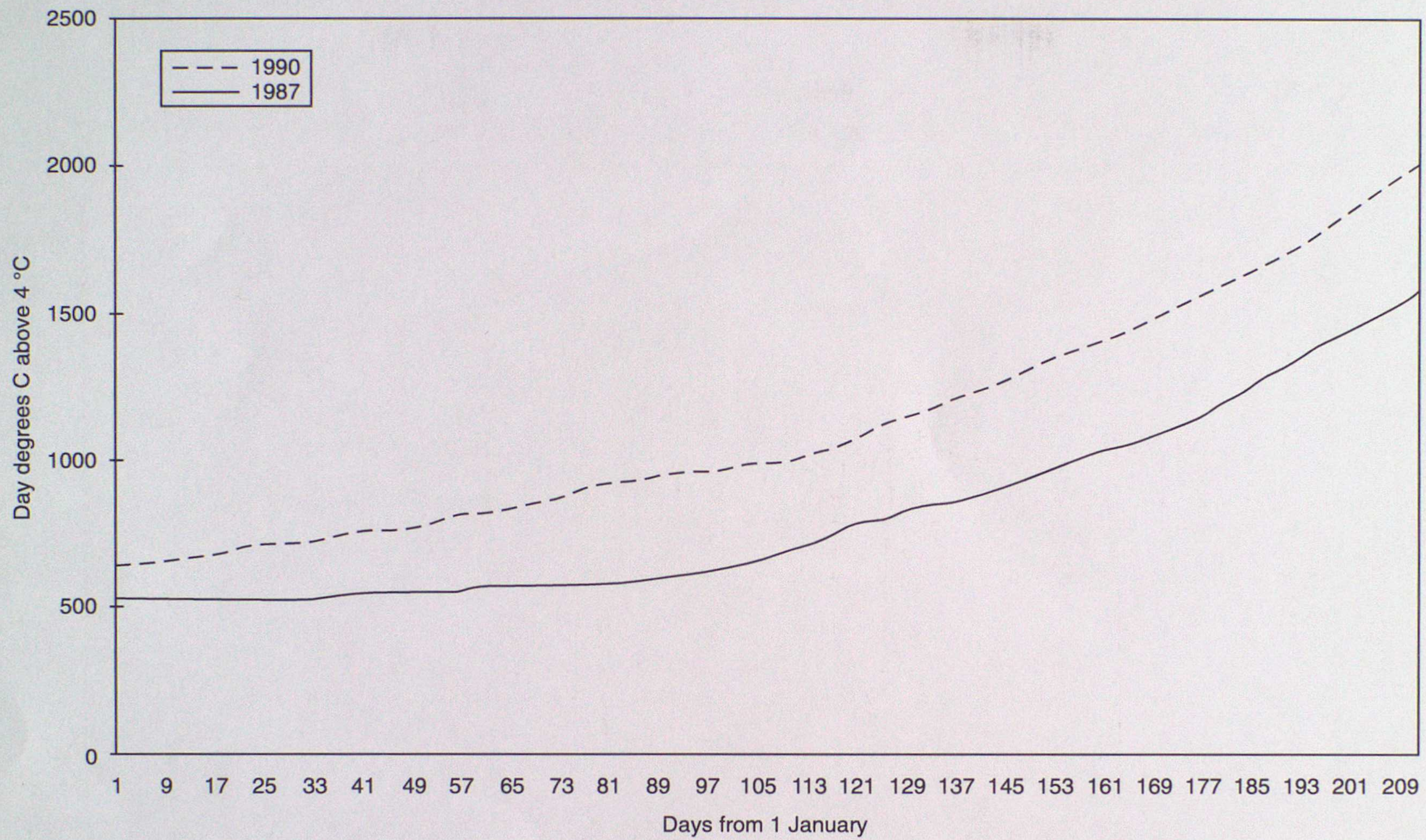

Figure E25.
Thermal time above base 4 °C from 1 September at Newport.

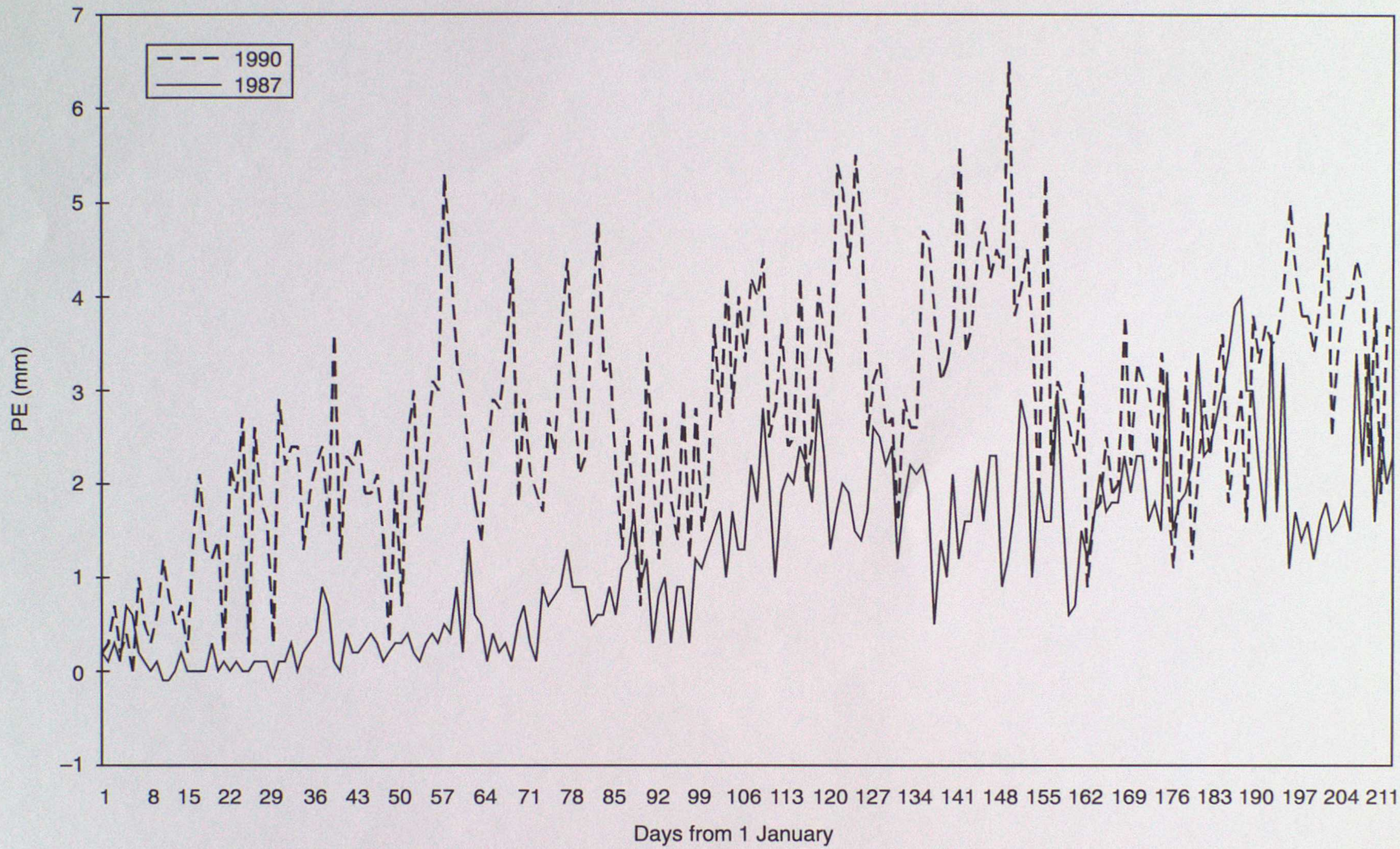

Figure E26.
Potential evaporation for oil-seed rape (MORECS 2) at Newport.

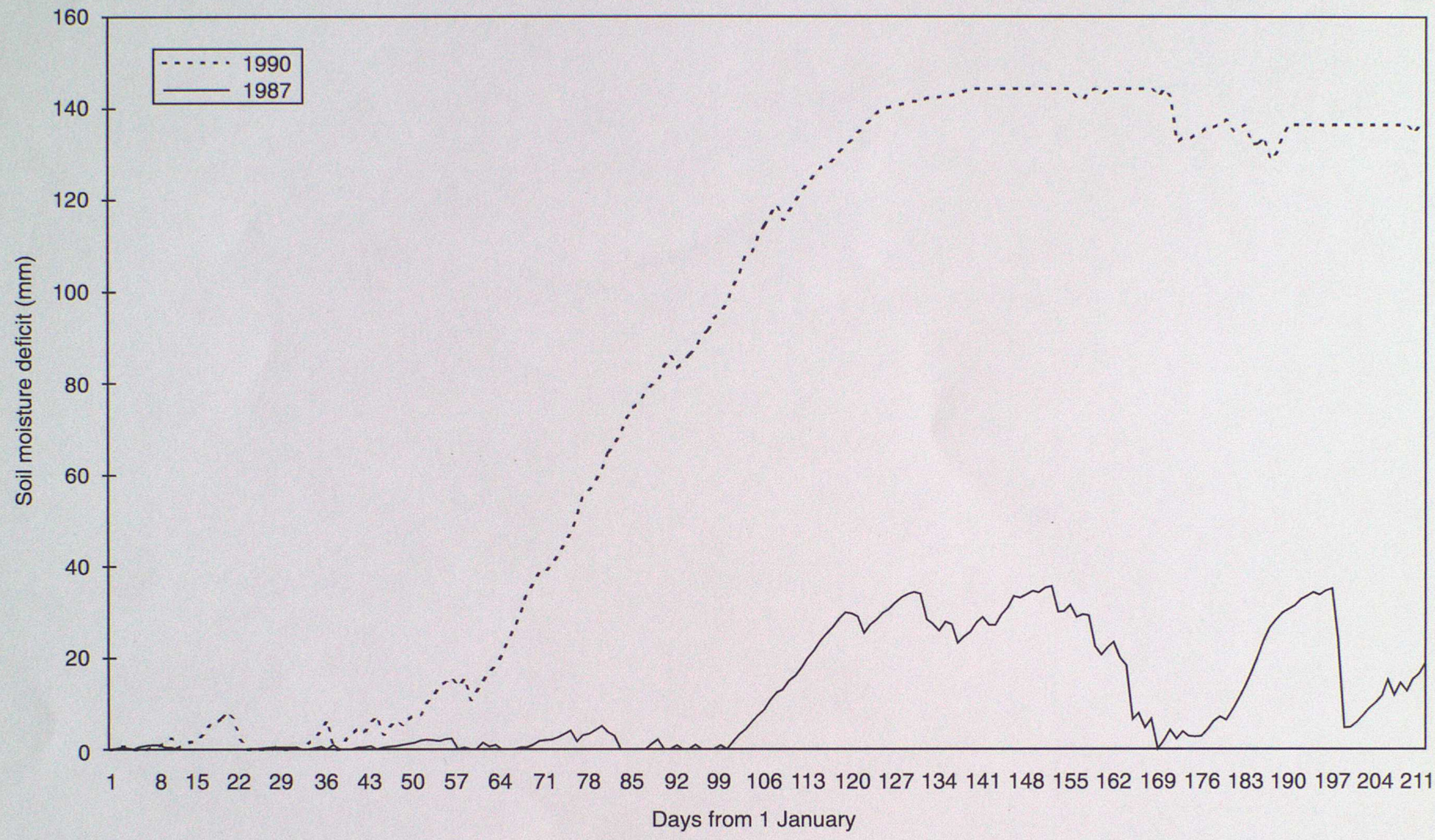

Figure E27.
Soil moisture deficit for oil-seed rape at Newport (MORECS 2, median soil).