METEOROLOGICAL OFFICE 1979

ESTIMATED SOIL MOISTURE DEFICIT AND POTENTIAL EVAPOTRANSPIRATION OVER GREAT BRITAIN

EXPLANATORY NOTES

INTRODUCTION

The Meteorological Office has prepared regular estimates of soil moisture deficits in map form and as tabular data for river authority areas for a number of years. This information, with a commentary relating soil moisture variations to changes in weather, has been distributed to interested authorities in Great Britain since September 1962.

Prior to 1971, soil moisture deficit reports were issued twice monthly, commencing in spring and ending when soil moisture deficits were made good, usually in autumn or early winter.

The map was drawn from estimates of soil moisture deficit made on the basis that each computing point represents unit area of terrain having the same areal proportions of 50 per cent short-rooted and 30 per cent long-rooted vegetation and 20 per cent riparian land. Deficits are assumed never to occur over riparian zones. In general, deficits become greater over long-rooted than over short-rooted zones and consequently persist there after they have been eliminated in short-rooted zones.

This system, whilst providing a useful general picture, cannot show the stage when 70 per cent of unit areas are at field capacity. This could give a misleadingly favourable view of the situation in terms of flood risk. Starting from the 1971 issues, therefore, a second map has shown deficits for root constant 75 mm only, appropriate to short-rooted vegetation including many types of grassland. From 1970 the reports have been suplemented once a month throughout the year by point estimates of potential evapotranspiration for a network of stations throughout the country; when these are issued independently of soil moisture deficit reports they may be supplemented by references to any unusually extended spell of dry weather.

EXPLANATORY NOTES

Soil moisture deficits are considered to have been set up when evapotranspiration exceeds precipitation and vegetation has to draw on reserves of water in the soil to satisfy transpiration requirements. Such deficits may occur in mid-winter but sustained deficits do not usually arise before spring. They commonly persist until autumn or early winter or even, in exceptional cases, throughout the following winter.

It is not unusual for the sustained period of soil moisture deficit to start in mid-month in spring and allowance has to be made for this by estimating evapotranspiration for the dry period. This estimation takes account of the change of rate of evapotranspiration throughout the month in question (particularly important in spring months when rates of evapotranspiration increase rapidly.)

A typical example would be

Month	Rainfall	Evapotranspiration	Accumulated soil moisture deficit
		millimetres	
15-30 April	Nil	30	30
May	50	79	59
June	75	96	80

Assessments of soil moisture deficits take account of the fact that vegetation has increasing difficulty in extracting moisture from the soil as accumulated potential evapotranspiration becomes greater than accumulated rainfall. It is assumed that each place at which rainfall is measured and evapotranspiration estimated is representative of a typical cross-section of catchment area of which 50 per cent is covered by short-rooted vegetation (grass etc.) which can draw up to 75 mm of moisture from the soil before actual evapotranspiration (and hence soil moisture deficit) starts falling below the potential, 30 per cent of the area is covered by long-rooted vegetation (trees etc.) which can draw freely on 200 mm of soil moisture, and 20 per cent of the area is riparian where the permanent ground water is so near the surface that evapotranspiration is never restricted.

For detailed study of specific catchment areas a much wider spectrum of root constants is used (seven values ranging from 12.5 to 200 mm) and an assessment is made of the actual vegetative cover. Allowance is also made in these more realistic models for the proportion of fallow soil, urban area and open water. Details are given in Hydrological Memorandum No. 38.

In the general model used for the soil moisture deficit report, account is taken of the extent to which actual evapotranspiration falls below potential when the difference, evaporation minus rainfall, reaches 75 mm and estimates have to be modified accordingly. The point at which actual evapotranspiration starts to fall below potential and the rate at which the discrepancy increases presents one of the most controversial aspects of soil physics. The scheme adopted was proposed by Penman (The dependence of transpiration on weather and soil conditions. J Soil Sci, Oxford, I, 1949, p.74); the paper gives a graph relating actual deficit to potential. Typical figures for a root constant of 75 mm are:

Potential	100	125	150	175	250 mm
Actual	99	109	113	115	121 mm

The modified procedure for estimating soil moisture deficit over a catchment area then becomes:

Month	Rainfall (R)	Evapotranspiration (E)	(R-E)	C_p	C_8	C_3	Catchment area
			Millimetres				
June	75	96	-21	80	80	80	64
July	13	100	-87	167	167	114	107
August	2	90	-88	255	237	122	132

Here C_p indicates the accumulated potential soil moisture deficit, C_8 the accumulated deficit over the zone with long-rooted vegetation and C_3 the accumulated deficit over the zone with short-rooted vegetation. It will be noted that accumulated deficits fall below the potential in July over the C_3 zone and in August over the C_8 zone. The 'areal' soil moisture deficit represents the average of the deficit over the C_3 zone (50 per cent of the total area) the deficit over the C_8 zone (30 per cent of the area) and zero deficit over the riparian zone (20 per cent of the area); hence the areal value is always at least 20 per cent less than the potential value.

When rainfall again starts exceeding evapotranspiration, usually in autumn, the soil moisture deficits are reduced by the amount by which rainfall exceeds evapotranspiration. It should be noted that the excess of rainfall over evapotranspiration will make an almost immediate contribution to run-off over the riparian zone (C_p) and that the zone with short-rooted vegetation (C_3), in general, will have deficits made good (and hence be contributing to run-off) before zone C_8.

The estimates of soil moisture deficit are based on observed rainfall and estimated evapotranspiration at a network of 200 stations. Rainfall data for most of these stations are received monthly and the soil moisture situation at the end of the month at each station is calculated as soon as records are received.

Data are not available from the majority of the 200 stations when estimates of soil moisture deficit are made at fortnightly intervals. Use is made of daily values of rainfall received up to date from about 55 official stations. These data are supplemented by data from about 25 Weekly Weather Report stations. These rainfall totals are fed into a computer and a weighted percentage value is obtained day by day for each of the 200 'soil mositure deficit' stations by reference to the nearest stations for which up-to-date values are available. The weighted percentage values are applied to the average annual rainfall at each of the 200 stations in order to obtain an estimate of rainfall in quantitative terms for the part month. In the winter six months (October to March) average evapotranspiration estimates are used and the slope of the annual march of the evapotranspiration curve is taken into account to obtain an estimate of potential evapotranspiration for a part month. In the summer six months (April to September) evapotranspiration is calculated for the part month using mean duration of sunshine at Official and WWR stations and the shortened form of Penman's equations (Ministry of Agriculture, Fisheries and Food, Technical Bulletin No. 16). Since interpolated values of rainfall and sunshine are used there is more uncertainty about the fortnightly published values of soil moisture deficit than for the end of month values calculated retrospectively, using observed rainfall values at the soil mosture deficit station. Revised values are used for subsequent calculations so there are no accumulative errors.

For a number of years the adjusted end-of-month values were obtained by using monthly totals of rainfall and of evapotranspiration. It became apparent that such a procedure could seriously under-estimate the accumulated potential soil moisture deficit if, for example, the bulk of a month's rainfall should fall in the last few days of the month following a very dry period in the earlier part of the month. From 1966, therefore, the estimates of soil moisture deficit have been made on a daily basis by computer. Additional complications arise with this system of daily accounting, particularly when the actual rate of evapotranspiration has fallen below the potential and alternating wet and dry spells occur. Such complications are dealt with in an article in the Meteorological Magazine, 96, 1967, p.97, where the estimation of soil moisture deficits is discussed more fully.

The Meteorological Office publication 'Estimated soil moisture deficit and potential evapotranspiration over Great Britain' opens with a short text drawing attention to important features in the distribution of soil moisture deficits and changes since the previous issue. These are related to noteworthly features of the weather. The text is followed by a table of estimated soil moisture deficits for a specified date and time for river authority and conservancy areas throughout England and Wales. The maps illustrate the deficits for the same date and time for England, Wales and Scotland. Estimates of potential evapotranspiration are supplied, in arrear, with the first bulletin of each month. These estimates are for the month-but-one before the month of issue (e.g. estimates of evapotranspiration for June are issued in August).

The estimates of evapotranspiration are calculated by the Penman formula. This formula, since its first publication (Proc R Soc, London, A, 193, 1948, p. 120) has received wide acclaim as one of the most soundly based methods of calculating evaporation using readily available meteorological data.

The merit of Penman's method lies in the combination of two of the classical aproaches to calculating evaporation, the energy-budget and the aerodynamic, thereby eliminating the requirement in either approach for the temperature of the evaporating surface, a quantity which is rarely measured on a routine basis and is usually difficult to obtain.

Although the formula has a sound physical basis a good deal of empiricism is also inherent particularly in deriving values for incoming and outgoing radiation in the energy-budget component. Much of this empiricism can be eliminated if measured amounts of global or net radiation are available but these are quantities which are obtainable for very few stations in the United Kingdom. Over the years since the first publication of the formula, the empirical constants in the basic equations have been changed from time to time and in quoting values derived from the formula it is important to state precisely what constants have been used.

The version of the formula used in deriving the values in the table is, with one important amendment, that published by Penman in J Agric Sci, Cambridge, 58, 1962, p.343. The calculations are carried out by computer and the formula is programmed to obtain the evapotranspiration (E) from a vegetated surface, the albedo of which is taken to be 0.25. This albedo is generally considered representative of grass, most agricultural crops in most phases of their development and deciduous woodlands in leaf (but not conifers); it is not appropriate to an open water surface and the values in the table cannot be considered representative of such a surface.

The formula is

$$E = \frac{\Delta H + \gamma E_a}{\Delta + \gamma}$$

where Δ is the slope of the saturation vapour pressure curve at the air temperature, γ is the hygrometric constant (taken as 0.49 in the program, where temperature is expressed in degrees Celsius and vapour pressure in millimetres of mercury).*

H is given by the equation

$$H = 0.75 R_a \left(0.18 + 0.55 \frac{n}{N}\right) - 0.95 \sigma T_a^4 \left(0.10 + 0.90 \frac{n}{N}\right)\left(0.56 - 0.092\sqrt{e_d}\right).$$

Here R_a is the amount of short-wave radiation reaching the outside of the earth's atmosphere expressed in millimetres of water evaporated per day (the simple latent-heat conversion is 59 cal/cm^2 = 1 mm of water evaporated), n/N is the ratio of observed hours of sunshine to possible hours, σT_a^4 is the theoretical black-body radiation in equivalent millimetres per day at mean air temperature T_a (expressed in kelvins) and e_d is actual vapour pressure (mm Hg) at T_a. The coefficient 0.95 is the important amendment referred to earlier and is intended to allow for vegetation not radiating as a perfect black body, following Budyko (The heat balance of the earth's surface, Leningrad, Gidrometeoizdat, 1956).

E_a is given by the equation

$$E_a = 0.35 (e_a - e_d) \left(1 + \frac{u_2}{100}\right)$$

where e_a is the mean saturation vapour pressure and e_d is the actual vapour pressure (both in mmHg) and U_2 is the run of wind in miles a day.

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* Conversions compatible with S1 units are: 1 mmHg = 1.3333 mb; 1 cal = 4.1868 ; 1 mile/day = 1.609 km/day; 1 mm water evaporated/day = 2.858 mW/cm^2.

120) ½

The data required for the calculation of evapotranspiration in the form adopted in the programme are: sunshine (actual hours per month), air temperature (^{o}C) and vapour pressure (mmHg), run of wind (derived from a frequency table of ranges of speeds), latitude and time of year (for the calculation of R_a and N). The programme can, however, accept other forms of data input.

All the values in the table are based on meteorological elements measured at least four times a day, averaged to give a mean value for the month. Values are also calculated but not published for stations which measure the required meteorological elements less frequently than four times a day and even for stations which measure once a day, only, at 09 GMT.

Most subscribers to the Estimated Soil Moisture Bulletin will be aware that in April 1978, a new and more versatile service MORECS (Meteorological Office Rainfall and Evaporation Calculation System) was inaugerated. The new system is modelled on more refined techniques including variable albedo, a wide range land use and real time estimates of potential evaporation; developments of the full Penman equation take into account aerodynamic and stomatal resistances, an allowance for soil heat flux and corrections to estimated long wave radiation. Other refinements include revised soil moisture extraction curves and allowance for intercepted precipitation. The revised formula will eventually replace the one described above in the routine calculation of potential evaporation for publication.

The MORECS system presents, for 40 x 40 km grid squares (ultimately to be replaced by 20 x 20 km squares), a series of maps showing meaned values for the centre point of each square of up to 14 hydrological and meteorological quantities as well as tabular soil moisture deficit for different crops and in due course different soils. The maps and tabular data are available in various options and are prepared weekly and at end of month. Details can be obtained from the address below.

It is intended that MORECS will eventually supersede the ESMD bulletin but the two are being continued in parallel for a few years, particularly as a climatology of ESMD is available for comparative purposes. It is intended to build up a climatology of MORECS.

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