Hey, J. S. 1946 *Nature*, **157**, 47.
Lovell, A. C. B. & Banwell, C. J. 1946 *Nature*, **158**, 517.
Martyn, D. F. 1946 *Nature*, **158**, 308.
McCready, L., Pawsey, J. L. & Payne-Scott, R. 1947 *Proc. Roy. Soc.* A, **190**, 357.
Nyquist, H. 1928 *Phys. Rev.* **32**, 110.
Pawsey, J. L., Payne-Scott, R. & McCready, L. 1946 *Nature*, **157**, 158.
Sander, K. F. 1947 *Nature*, **159**, 506.
Schottky, W. 1922 *Ann. Phys., Lpz.*, **68**, 157.
Southworth, G. C. 1945 *J. Franklin Inst.* **239**, 285.

Natural evaporation from open water, bare soil and grass

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[Plate 3]

Two theoretical approaches to evaporation from saturated surfaces are outlined, the first being on an aerodynamic basis in which evaporation is regarded as due to turbulent transport of vapour by a process of eddy diffusion, and the second being on an energy basis in which evaporation is regarded as one of the ways of degrading incoming radiation. Neither approach is new, but a combination is suggested that eliminates the parameter measured with most difficulty—surface temperature—and provides for the first time an opportunity to make theoretical estimates of evaporation rates from standard meteorological data, estimates that can be retrospective.

Experimental work to test these theories shows that the aerodynamic approach is not adequate and an empirical expression, previously obtained in America, is a better description of evaporation from open water. The energy balance is found to be quite successful. Evaporation rates from wet bare soil and from turf with an adequate supply of water are obtained as fractions of that from open water, the fraction for turf showing a seasonal change attributed to the annual cycle of length of daylight. Finally, the experimental results are applied to data published elsewhere and it is shown that a satisfactory account can be given of open water evaporation at four widely spaced sites in America and Europe, the results for bare soil receive a reasonable check in India, and application of the results for turf shows good agreement with estimates of evaporation from catchment areas in the British Isles.

List of symbols used

x, y, z	Co-ordinate axes downwind, acrosswind and vertical.
u_z	Mean horizontal wind velocity in x direction measured at height z; usually in miles/day.
T_s, T_a, T_d	Temperature of surface, air and dewpoint; usually °F.
e_s, e_a, e_d	Saturation vapour pressure at above temperature; usually in mm. Hg.
h	Relative humidity $= e_d/e_a$.
Δ	de_a/dT_a.
ϕ	$(e_s - e_a)/(e_s - e_d)$.
α	Constant defining hydrolapse.
β	Bowen's ratio $= \gamma(T_s - T_a)/(e_s - e_d)$.

γ	Constant of wet and dry bulb hygrometer equation; in °F and mm. Hg, $\gamma = 0{\cdot}27$.
E_0, E_B, E_T	Evaporation rate from open water, bare soil and turf; usually in mm./day.
E_a	Value of E_0 obtained by putting $e_s = e_a$ in sink strength formula.
R_C	Short-wave radiation from sun and sky; usually in evaporation equivalent of mm./day.
R_A	Angot value of R_c for a completely transparent atmosphere.
r	Radiation reflexion coefficient. (Also used for runoff without any possibility of confusion.)
$m/10$	Fraction of sky covered by cloud.
n/N	Ratio of actual/possible hours of sunshine.
H	Net radiant energy available at surface.
K, S, C	Parts of H used in convective transfer to air, storage in water, conduction to surround.
5B, 16T	Depths to water-table (in.) and type of cover (bare, turf).
λ	Specific yield of soil.
R, D	Rainfall, drainage.
B	Beaufort wind force.

1. Introduction

Three kinds of surface are important in the return of rain to the atmosphere. For extended areas of land, they are, in order of importance: vegetation, on which plant leaves act as transpiring surfaces; bare or fallow soil, from which water evaporates at, or just below, the soil-air interface; and open water, from which evaporation takes place directly. Although the last may be of predominant importance locally, e.g. in attempting to assess the water balance of lakes and reservoirs, the chief justification of the great attention given to it (see § 2, below) is found in the opportunity it presents of providing a reproducible surface of known properties. Because of this, it is convenient to approach the problems of the dependence of evaporation from bare and cropped soil on weather conditions through a study of evaporation from open water, seeking an absolute relation between weather elements and open water evaporation, and comparative relations between losses from the soil and losses from open water exposed to the same weather.

Evaporation from bare soil involves complex soil factors as well as atmospheric conditions: transpiration studies add to these further important physical and biological features, for a plant's root system can draw on moisture throughout a considerable depth of soil, its aerial parts permit vapour transfer throughout a considerable thickness of air, and its photo-sensitive stomatal mechanism restricts this transfer, in general, to the hours of daylight. A complete survey of evaporation from bare soil and of transpiration from crops should take account of all relevant factors, but the present account will be largely restricted to consideration of the early stages that would arise after thorough wetting of the soil by rain or irrigation, when soil type, crop type and root range are of little importance.

2. The estimation of evaporation from weather data

Two requirements must be met to permit continued evaporation. There must be a supply of energy to provide the latent heat of vaporization, and there must be some mechanism for removing the vapour, i.e. there must be a sink for vapour. Analytical attacks on the problem start from one of these two points and it is convenient to consider the latter first as it has been the more popular.

(a) *Sink strength*

(i) *Empirical equations*

Until recent years the approach was empirical, a hundred years' work since Dalton having produced little improvement in the form of equation he gave. In essentials it is

$$E = (e_s - e_d) f(u), \tag{1}$$

where E is the evaporation in unit time, e_s is the vapour pressure at the evaporating surface, e_d is the vapour pressure in the atmosphere above, and $f(u)$ is a function of the horizontal wind velocity. For water, e_s is known if the surface temperature is known. Of the many empirical formulae cast into this form, one due to Rohwer (1931) summarizes results of very intensive work at Fort Collins, Colorado, at 5000 ft. above sea-level. Other things being equal, Rohwer found a small variation of evaporation rates with atmospheric pressure, and reduced to conditions at sea-level, his equation for the daily rate from an open water surface 3 ft. square is

$$E = 0{\cdot}40(e_s - e_d)(1 + 0{\cdot}27u_0) \text{ mm./day}, \tag{2}$$

where vapour pressures are in mm. mercury, and wind speed at ground level is in m.p.h. Examining the effect of size of surface on evaporation rates, over a period of 485 days, he compared the observed values of evaporation from a large surface 86 ft. diameter with the estimates based on (2), and found the mean value of observed/estimated to be 0·77. There is some bias here, however, for the average wind speed over the whole period was only 1·50 m.p.h., and examination of the individual daily records shows that on the rare occasions of a wind speed in excess of 3 m.p.h. the correction factor is nearly unity. The ground wind velocity, u_0, is an extrapolated value estimated from a number of readings at various heights, and if from Rohwer's u, z curve we interpolate at 2 m., the relation becomes

$$E = 0{\cdot}40(e_s - e_d)(1 + 0{\cdot}17u_2) \text{ mm./day}, \tag{3}$$

and except at very low wind speeds might be expected to apply to large open water surfaces.

(ii) *Aerodynamic equations*

As an alternative to this empirical treatment an aerodynamical approach has been made in recent years. A simple treatment (Penman 1940) showed that the right order of magnitude could be obtained by assuming that the main resistance to the evaporation current is provided by a thin layer of air (*c.* 1 to 3 mm. thick) next to the surface, in which air movement is essentially non-turbulent, and vapour movement across which is by a process of molecular diffusion. The more formal treatment, having wider implications than the solution of evaporation problems, has considered the turbulent mixing and transport of the vapour outside this sublaminar boundary layer, and it attempts to take into account the dependence of evaporation rates per unit area upon size and shape of the test area as well as upon weather elements. An account of this work is given by Brunt (1939) up to and including the work of O. G. Sutton (1934). Extension of Sutton's work by W. G. L. Sutton (1943) and Pasquill (1943) has given an expression for the *total* evaporation from a rectangular strip of length x_0 downwind and width y_0:

$$E(x_0, y_0) = C(e_s - e'_d)\, u_2^{0\cdot76} x_0^{0\cdot88} y_0, \tag{4}$$

where C is a constant related to the absolute temperature, e'_d is the vapour pressure of the air at a height great enough to be unaffected by the evaporation, and u_2 is the wind velocity at $z = 2$ m. Although e'_d is unobservable, it has been possible to use the same general theory to express the shape of the hydrolapse, and to set $(e_s - e_d) = \alpha(e_s - e'_d)$ where e_d is the measured value at screen height, and α ($\doteqdot 0\cdot52$) is almost independent of u and x_0. Differentiating (4), the rate of evaporation *at* x_0 is obtained, and, substituting numerical values appropriate to zero temperature gradient, it becomes

$$E = 0\cdot11(e_s - e_d)\, u_2^{0\cdot76} x_0^{-0\cdot12}\, \text{mm./day}. \tag{5}$$

In the open it is impossible to fix the position of the leading edge, but arbitrarily putting $x_0 = 1\cdot6 \times 10^6$ cm. (10 miles), the evaporation rate becomes

$$E = 0\cdot376(e_s - e_d)\, u_2^{0\cdot76}\, \text{mm./day}, \tag{6}$$

where e_s and e_d are in mm. mercury, and u_2 is now in miles/hr. If u_2 is measured in miles/day—a practical convenience—the rate is

$$E = 0\cdot033(e_s - e_d)\, u_2^{0\cdot76}\, \text{mm./day}. \tag{6a}$$

Notes. (1) The assumption of zero temperature gradient involves the identity of e_s and e_a, where e_a is the saturation vapour pressure at the mean air temperature; $e_s - e_d$ then becomes $e_a(1-h)$.

(2) A tenfold increase in x_0 will decrease E in the ratio $(1/10)^{0\cdot12}$, i.e. to $1/1\cdot3$, and the constant in (6*a*) will become 0·025.

(*b*) *Energy balance*

Certain simplifying assumptions are needed; where they are known to be reasonable, reliable estimates of evaporation are possible. Using as the unit of energy the amount required to evaporate 1/10 g. of water at air temperature (59 cal.) it is possible to build up the following expression for the heat budget, H, taking into account the incoming short-wave radiation from sun and sky, and the long-wave exchanges between earth and sky (Brunt 1939; equation 15, p. 136; equation 25, p. 144):

$$H = R_C(1 - r - \mu) - \sigma T_a^4(0\cdot56 - 0\cdot092\sqrt{e_d})(1 - 0\cdot09m), \tag{7}$$

where R_C is the measured short-wave radiation/cm.^{2}/day,

r is the reflexion coefficient for the surface,

μ is the fraction of R_C used in photosynthesis,

σT_a^4 is the theoretical black-body radiation at T_a °K,

e_d is in mm. mercury,

and $m/10$ is the fraction of sky covered with cloud.

Using the convenient symbols of Cummings & Richardson (1927), the heat budget is used in evaporation, E, heating of the air, K, heating of the test material, S, and heating of the surroundings of the test material, C, i.e.

$$H = E + K + S + C. \tag{8}$$

Over a period of several days, and frequently over a single day, the change in the stored heat, S, is negligible compared with other changes and the same may be true of the heat conducted through the walls of the test material container. Thus, (8) can often be safely reduced to

$$H = E + K. \tag{9}$$

The transport of vapour and the transport of heat by eddy diffusion are, in essentials, controlled by the same mechanism, and apart from the differences in the molecular constants, the one is expected to be governed by $(e_s - e_d)$ where the other is governed by $(T_s - T_a)$. To a very good approximation, therefore, it is possible to write down the ratio of K/E in the form

$$K/E = \beta = \gamma(T_s - T_a)/(e_s - e_d), \tag{10}$$

where β, the ratio symbolized by Bowen (1926) as R, has the value -1 in the standard wet and dry bulb hygrometer equation, and γ is the standard constant of this equation. In °F and mm. Hg, $\gamma = 0{\cdot}27$.

Thus $$H = E(1+\beta), \quad E = H/(1+\beta). \tag{11}$$

Of the terms on the right-hand side of (7), the radiation term will rarely be directly measurable, but for periods of the order of a month or more it can be estimated from duration of sunshine. Angot has given tables of the total radiation to be expected if the atmosphere were perfectly transparent (Brunt (1939), p. 112), and there appears to be a general correlation between R_C/R_A and n/N in the form $R_C/R_A = a + bn/N$, where n/N is the ratio actual/possible hours of sunshine. For Virginia, U.S.A., Kimball (1914) finds $a = 0{\cdot}22$, $b = 0{\cdot}54$; for Canberra, Australia, Prescott (1940) finds $a = 0{\cdot}25$, $b = 0{\cdot}54$. At Rothamsted, monthly values over the period 1931–40 lead to $a = 0{\cdot}18$, $b = 0{\cdot}55$, with a suggestion of a seasonal variation. Using these latter constants we have

$$R_C = R_A(0{\cdot}18 + 0{\cdot}55n/N). \tag{12}$$

In terms of the maximum to be expected (R_N; for $n = N$), equation (12) becomes

$$R_C = R_N(0{\cdot}25 + 0{\cdot}75n/N), \tag{12a}$$

agreeing with the form given by Angstrom for Stockholm (Brunt (1939), p. 127).

The value of μ is very small (*c.* 0·005) and can be neglected. The value of r will vary with season and type of surface. For water its annual mean will be about 0·06 in the British Isles; for bare soil, about 0·10; and for turf might be about 0·20 (Geiger (1927) quoting Angstrom). Note that r and β will be the only effective factors in (7) discriminating between the different types of surface.

The terms expressing the net flow of radiation to and from a cloudless sky are due to Brunt and are based on the mean values of the constants obtained in six correlations of the energy flow with mean air temperature. Sverdrup (1945) gives a diagram indicating values of the same order but with slightly greater values of $\sigma T^4 f(e_d)$. The uncertainty here, however, is negligible compared with that arising from the cloudiness term. It is obvious that cloud control of long-wave radiation must depend upon cloud type, and as a provisional expedient to make some allowance for this it is proposed to set $m/10 = 1 - n/N$. Equation (7) therefore reduces to

$$H = E(1+\beta) = (1-r)\,R_A(0{\cdot}18 + 0{\cdot}55n/N) - \sigma T_a^4(0{\cdot}56 - 0{\cdot}092\sqrt{e_d})\,(0{\cdot}10 + 0{\cdot}90n/N) \tag{13}$$

where $R_A(0{\cdot}18 + 0{\cdot}55n/N)$ is to be replaced by R_C when this is known. The parameters represented on the right-hand side of (13) are easily determined; to obtain E it is necessary to obtain β, which involves knowing the surface temperature (equation 10). The sink strength approach also involves this knowledge, and although arrangements can be made to measure it experimentally, it is desirable to eliminate it for the prediction of evaporation or for a survey of evaporation as a climatic element.

(*c*) *Combination of sink strength and energy balance*

From (1), expected to take the form of (6) or (6*a*), we have

$$E = (e_s - e_d)\,f(u). \tag{1}$$

Let E_a be the value of E obtained by putting e_a instead of e_s. Then

$$E_a = (e_a - e_d)\,f(u),$$

i.e.

$$E_a/E = 1 - (e_s - e_a)/(e_s - e_d) = 1 - \phi \text{ say.} \tag{14}$$

From (10) and (11);

$$E = H/(1+\beta) = H/[1 + \gamma(T_s - T_a)/(e_s - e_d)].$$

If we set $T_s - T_a = (e_s - e_a)/\Delta$, where Δ is the slope of the $e:T$ curve at $T = T_a$, then

$$H/E = 1 + \gamma(e_s - e_a)/\Delta(e_s - e_d) = 1 + \gamma\phi/\Delta. \tag{15}$$

From (14) and (15);

$$E = (H\Delta + E_a\gamma)/(\Delta + \gamma), \tag{16}$$

$$e_s = (e_a - \phi e_d)/(1 - \phi), \tag{17}$$

i.e. E can be estimated from air conditions only, and, if required, an estimate of surface temperature can be obtained that might be useful outside evaporation studies.

In addition to the constants, readily obtainable from standard sources, the weather parameters needed are mean air temperature, mean dewpoint, mean wind velocity at a standard height and mean duration of sunshine.

3. Rothamsted experiment 1944, 1945

(a) *Experimental site*

Experiments have been carried out in the meteorological enclosure at Rothamsted, situated at about 420 ft. above O.D. in open parkland in the Chiltern Hills. The enclosure includes a brick-lined pit, 8 ft. deep and 20 ft. diameter, around which twelve cylinders were set in the soil in 1924, five of them being filled with a sandy loam from Woburn (Bedfordshire), the soil texture being uniform throughout. The cylinders are 6 ft. deep and 2 ft. 6 in. diameter and are made of cast iron lined with a $\frac{1}{2}$ in. layer of bitumen painted concrete; the bottoms have a slope down to an outlet pipe accessible from the pit. (See figure 1 and figure 7, plate 3.)

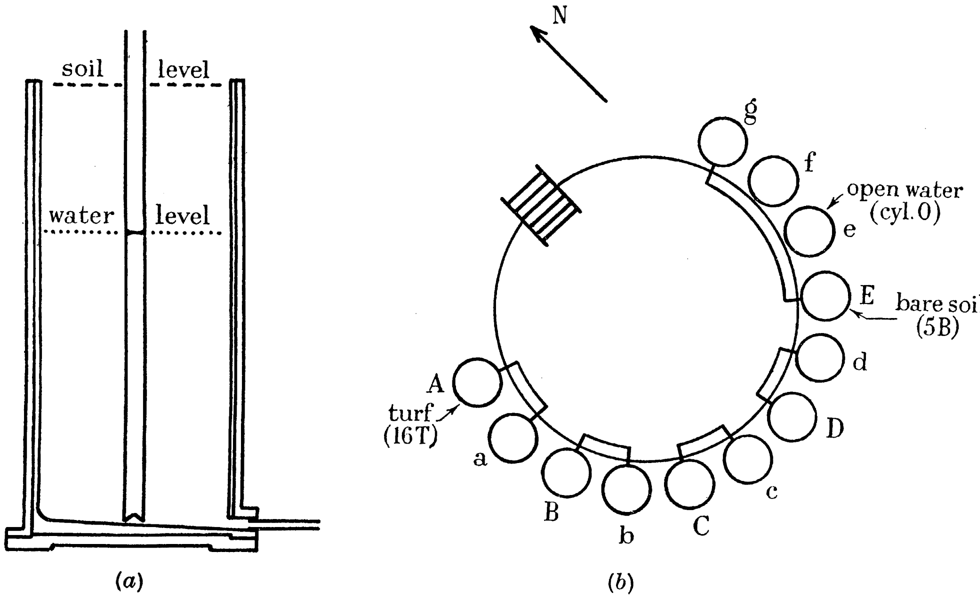

Figure 1. (a) Section of cylinder, and (b) plan of the pit.

The soil was left to settle and weather for 16 years so that some semblance of natural structure could be attained and by May 1940 the settlement amounted to 6 in. This was made good by a further supply of Woburn soil, experimental work was done in 1941 and 1942 and in the spring of 1944 there was a further slight topping up in preparation for the work now to be described.

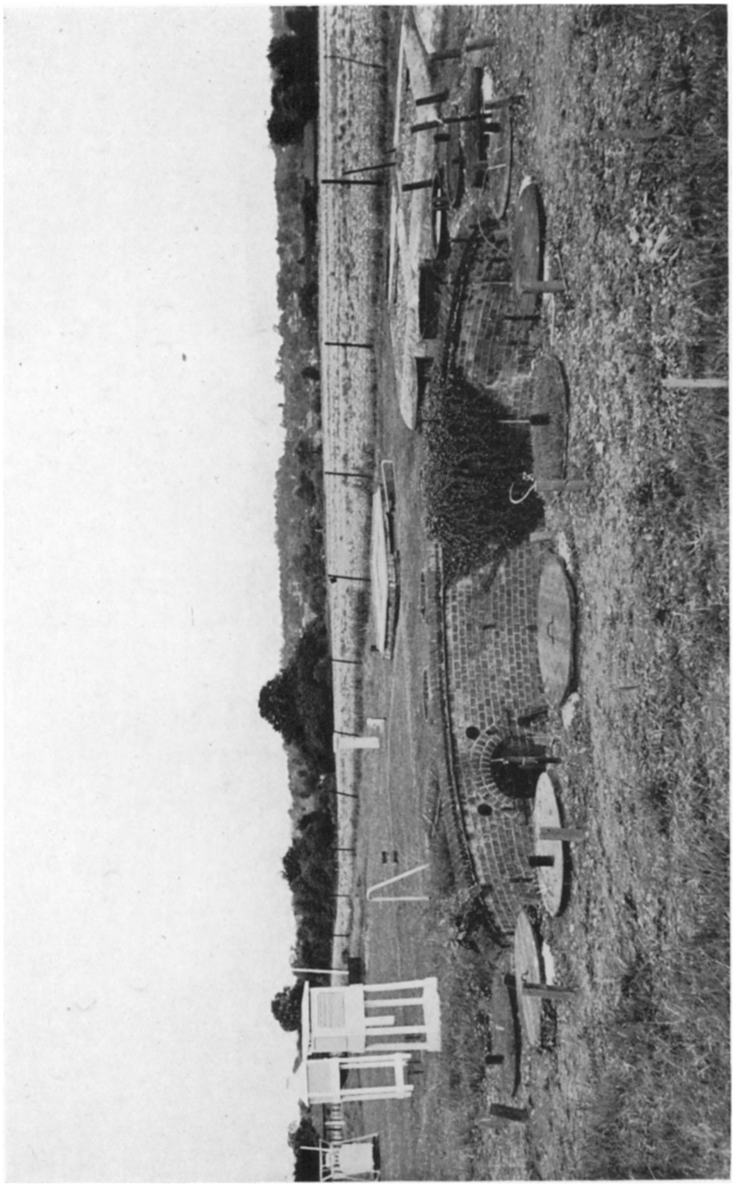

FIGURE 7. The experimental site June 1944, looking north-east.

(*Facing p.* 126)

Ten cylinders were joined up in pairs at the outlets, each soil cylinder being connected to an unfilled cylinder referred to below as the 'minor', so forming a set of U tubes. Figure 1 shows the arrangement schematically, with three cylinders labelled (O, 5B and 16T). These are the main ones to be discussed and were the same in both years; changes were made in the others early in 1945. Waterproof covers were provided for the minors to prevent entry of rain and to reduce evaporation losses to negligible amounts. On A and C turves were laid in April 1944 and on D in March 1945; the other soil surfaces were kept bare.

At the outset the minors were filled with water until the soil or turf surfaces were flooded and then water was run out until the water-table had reached a pre-determined depth below the soil surface. The depths and the nature of the surface are given in table 1:

TABLE 1. DEPTHS (IN.) OF WATER-TABLE AND NATURE OF SURFACE

cylinder ...	A	B	C	D	E
1944	16 (T)	16 (B)	10 (T)	10 (B)	5 (B)
1945	16 (T)	24 (B)	24 (T)	36 (T)	5 (B)

Cylinder e was filled to near the brim and the level kept at about 1 in. below. This was the first open water standard, referred to as cylinder O. In the early summer of 1945 a tank of sheet galvanized iron, 2 ft. 6 in. diameter and 2 ft. deep was supplied by the Meteorological Office and was set up at the north end of the enclosure about 50 yd. north of the pit. A hole 1 ft. 9 in. deep was dug into which the tank fitted firmly, and the water-level was kept at or near ground level, so leaving a projecting rim of 3 in. This tank, referred to as tank MO, had the same area as the cylinder but was shallower, had a thinner and more conducting wall material, was completely surrounded by turf-covered soil whereas the other had the pit on one side, and had a higher effective rim.

Ground level round the cylinders had been raised so that soil level was the same inside and out except on one side of cylinder O where the topping up was not complete; for all the cylinders there was a big discontinuity in surface on the pit side and although the pit should have been roofed in, it was not practicable at the time and a major objection to the experimental site had to be accepted as unavoidable. Figure 7, plate 3, shows the exposure to the north-east and the disposition of some of the other components of the enclosure; in the centre, beyond the pit, is the large rain gauge (1/1000 acre) used for rainfall values employed below, and to the right of it are visible two of the bare drain gauges on which earlier Rothamsted work was based. The general exposure here is good, although the presence of the large gauges might affect local eddies with east and north-east winds. The general exposure to north-west was equally good, that to south-west a little worse, and that to south-east poorest of all due to an extended belt of trees, the nearest being about 80 yd. away.

The surround varied during the experiment. The local exterior topping up remained bare for a while, but a crop of weeds soon developed and gave a local cover nearly enough equivalent to the turf of the enclosure. By the summer of 1945 there was a fair amount of grass in this and it was possible to cut it with a mower. Growth was very rapid during 1945 and part of the surround, too rough for a mower, got out of hand and for a while there was a stand of tall grass on the west side which may have had an adverse effect on transpiration from cylinder A (16T). In both years the field to the east was sown with mangolds giving a green cover from June until late autumn, at which time the soil surface was moist and remained moist for the remainder of the winters. The field to north and west carried an oat crop in 1944, about 1 ft. high in May, 3 ft. high throughout July and harvested in early August; the undersown clover then provided a green cover for the remainder of the season, was grazed during 1945, but grew away from the animals and a hay crop was eventually taken from it. To the south there was a pasture, kept short by grazing. Thus, except for short periods, the experimental surfaces could be reasonably described as being in the midst of an extensive area of short vegetation and as long as this transpired at maximal rate, then for so long did the experimental conditions come close to satisfying the basic assumptions from which equation (6) was derived.

(b) *Measurements and calibrations*

In addition to the normal 09.00 observations of a third-order meteorological station, supplementary measurements were made.

(i) *Temperature.* Mercury-in-steel thermographs were set up on cylinders C, D, E and O; that on D was transferred to tank MO in June 1945. The long bulbs were horizontal and were either pressed into the soil or supported in the water so that about half was below the surface and half above the surface; the water bulbs had sheaths of muslin to ensure that they were always wet all over. They were calibrated in place, and in all cases the corrected 'surface' temperature is more truly the mean temperature of the top few mm. of soil or water. To find the daily mean a smooth curve was drawn through the thermogram and a mean of six readings at 4 hr. intervals found; this was corrected from the calibration curve and the corresponding value of the saturation vapour pressure taken as the daily mean value of e_s.

Only one value of the dewpoint was obtained per day and although this was found to be adequate for long period surveys it was not always adequate for individual days, particularly where there was a pronounced change during the day. The Dunstable Branch of the Meteorological Office kindly supplied estimates of the dewpoint at 6 hr. intervals for each day and from these it was possible to see the way in which the dewpoint had changed in a given period of 24 hr. and to weight the Rothamsted values accordingly. Obtaining a reliable daily mean value of the dewpoint remains one of the main experimental problems to be solved.

The mean air temperature is never of first order of importance and it has been sufficient to take the conventional mean of maximum and minimum for this parameter.

(ii) *Wind.* A three-cup anemometer was set up at 2 m. in the south-west corner of the enclosure in 1944, and was moved to the middle of the enclosure early in 1945 so as to be about half-way between the pit and the new MO tank. The scale reading was read once daily, and in view of this it was an obvious convenience to use miles/day as the unit of wind velocity (equation (6*a*); figures 2 and 3). The instrument was calibrated in December 1944 in terms of a similar instrument with smaller cups, with which a calibration curve was supplied. The curve was non-linear at low speeds and calibration of the experimental instrument is consequently uncertain in this region: table 2 shows the result:

TABLE 2. CALIBRATION OF ANEMOMETER (MILES/DAY)

observed	0	30	60	90	120	150	210	270
corrected	38	50	78	106	133	161	215	272

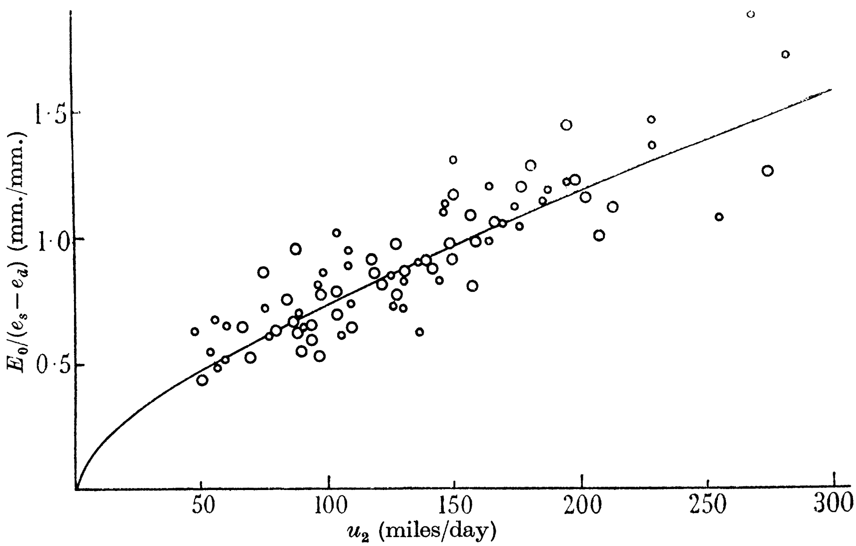

FIGURE 2. Daily evaporation per unit partial pressure difference for open water surface (cylinder O). The curve is: $E_0/(e_s-e_d) = 0{\cdot}033\,u_2^{0{\cdot}68}$, ○ 1944, ◯ 1945.

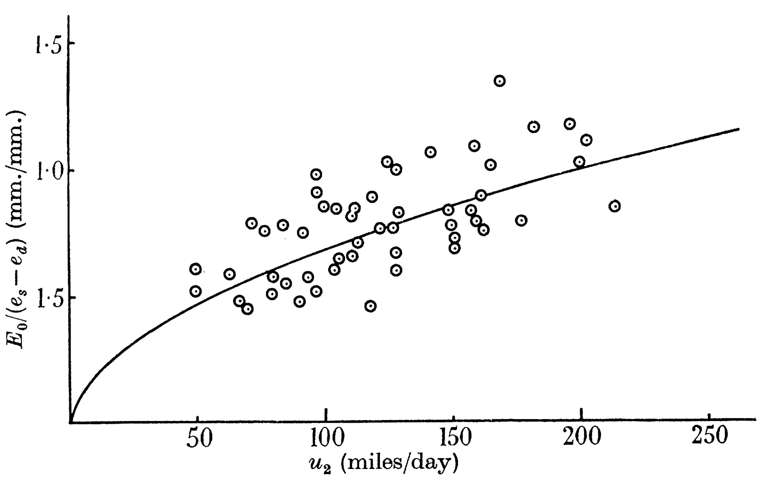

FIGURE 3. Daily evaporation per unit partial pressure difference for open water surface (tank MO). The curve is: $E_0/(e_s-e_d) = 0{\cdot}065\,u_2^{0{\cdot}54}$.

A Dines wind recorder on the laboratory roof, about $\frac{1}{4}$ mile away, was used to estimate direction and variation of wind speed during the day, where necessary.

(iii) *Radiation.* A continuous record of radiation intensity on a horizontal surface was obtained each day, the total area under the trace measured by planimeter and the figure so obtained converted to the equivalent number of mm. of water that the total energy would evaporate at air temperature.

The duration of sunshine was obtained from a Campbell-Stokes recorder.

(iv) *Evaporation.* Daily measurements were made of the depth of the water-levels below arbitrary zeroes.

Cylinders A, B, C and D. A rigid cradle was built into the top of the minor into which could be fitted a framework carrying a screw ending in a sharp pointed dip-stick. The screw carried a scale that moved past a fixed index mark and readings could be made to better than $\frac{1}{5}$ mm. except on very windy days.

Cylinders E and O. Measurements here were somewhat cruder. A solid straight edge was placed across the top of the minor in a marked position and, by means of a guide, a pointed rule was slid down until it just touched the water surface. With care, readings could be reproduced to within about $\frac{1}{5}$ mm., and in the major part of the experiment this was adequate accuracy.

Tank MO. A hook gauge reading to $\frac{1}{100}$ in. was used.

Changes in level are due to evaporation or rainfall, both being excluded from the minors. A fall in level takes place in both arms of the U system when evaporation occurs, so that for a change in minor level of δz, the total evaporation is greater, and may be set equal to $\delta z(1+\lambda)$, where λ is the specific yield of the soil with water-table at z cm. below the surface. If, over a period, the measured rainfall is R, then the total evaporation is given by

$$E = \delta z(1+\lambda)+R. \tag{18}$$

As λ is a function of z, measurements were made to give the values in table 3.

TABLE 3. SPECIFIC YIELD OF SOIL

depth of water-table (in.)	5	10	16	24	36
specific yield, λ (cm./cm.)	0·02	0·04	0·10	0·13	0·13

4. RESULTS FOR INDIVIDUAL DAYS

(a) *Open water: sink strength*

Equation (6*a*) was tested by plotting $E_0/(e_s-e_d)$ against u_2. Figure 2 shows the result for cylinder O with the 1944 and 1945 data distinguished, figure 3 shows the result for tank MO from mid-June 1945, and in figure 4 are given values of $\Sigma E_0/\Sigma(e_s-e_d)$ for wind speed ranges sufficiently wide to include at least four observations in the summations. The data represented in these figures have been selected as follows: (i) rain days have been excluded as there is some uncertainty about the uniformity of rainfall distribution over the site; on such a day the fall in level is made up of evaporation minus rainfall. (ii) For cylinder O, only those days have been used in which $E_0 > 2{\cdot}5$ mm. and $(e_s - e_d) > 2{\cdot}5$ mm.; for tank MO, to increase the number of available results, the limits were lowered to 2·0 mm. The experimental errors tend to be absolute and the uncertainty in the ratio increases greatly as E_0 and Δe become very small.

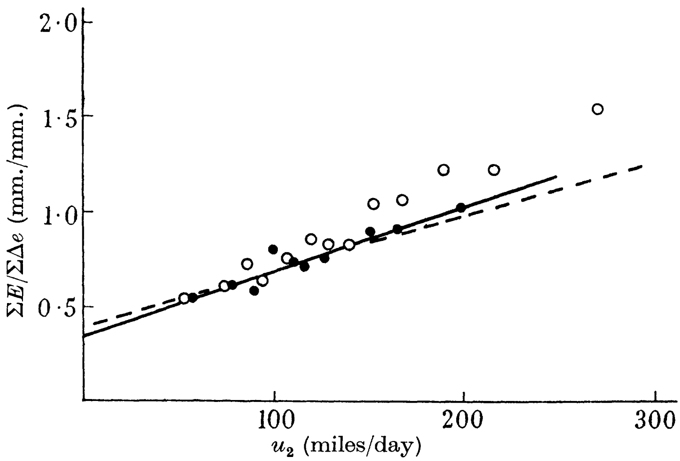

FIGURE 4. Mean daily evaporation per unit partial pressure difference for open water (groups of days having approximately the same average wind speed). The continuous line is: $E_0/(e_s - e_d) = 0{\cdot}35(1 + 9{\cdot}8 \times 10^{-3} u_2)$. ○ cylinder O; —●— tank MO; --- Rohwer.

The scatter in figures 2 and 3, although not very much worse than that obtained by other workers doing indoor experiments, is considerable. A number of obvious contributory factors have been examined and shown to be of slight effect: dryness of the surround, wind distribution during the day, height of rim and season of the year. The main sources are undoubtedly the meteorological observations themselves; in increasing order of importance they are: dewpoint and surface temperature determinations and wind velocity measurements. Concentrating on the last, it is doubtful whether a measurement at a single height and the assumption of zero velocity at ground level are sufficient to define the wind velocity profile even over a smooth surface; they cannot be expected to take account of the local turbulence introduced by many obstructions and surface irregularities. These will vary with wind direction, and an analysis of the cylinder O results showed that all high values of $E/\Delta e$ at high u_2 were for days with north-east winds, i.e. days in which the local exposure would be most conducive to extra turbulence. It seems, therefore, that in spite of their greater scatter, the tank MO results are probably a better guide to a general law than the cylinder O results, and this is supported by the comparison (figure 4) with Rohwer's results. (Because of the scatter it is probable that the mean curves do not differ significantly.) The mean curves show that there is a linear relationship between $E/(e_s - e_d)$ and u_2, but for comparison with the theoretical form two curves could be fitted: (i) through the overall mean value of $E/\Delta e$ and of u_2, a curve $E/\Delta e = bu_2^{0{\cdot}76}$ (cf. equation 6a) and, (ii) through the two general means obtained from the groups of points lying to the left and right of the overall mean, a curve $E/\Delta e = au_2^n$. The results, in decreasing order of efficiency, are given in table 4.

TABLE 4. VALUES OF $f(u)$ IN $E_0 = (e_s - e_d) f(u)$

	cylinder O	tank MO	Rohwer*
best	$0{\cdot}30(1+14{\cdot}2\times10^{-3}u_2)$	$0{\cdot}35(1+9{\cdot}8\times10^{-3}u_2)$	$0{\cdot}40(1+7{\cdot}1\times10^{-3}u_2)$
good	$0{\cdot}033u_2^{0{\cdot}68}$	$0{\cdot}065u_2^{0{\cdot}54}$	—
fair	$0{\cdot}021u_2^{0{\cdot}76}$	$0{\cdot}019u_2^{0{\cdot}76}$	—

The curves drawn in figures 2 and 3 are the 'good' curves, wind velocities being in miles per day.

From the above, it is concluded that: (i) the best form of (1) for practical use is

$$E_0 = 0{\cdot}35(1+9{\cdot}8\times10^{-3}u_2)(e_s-e_d)\ \text{mm./day},\quad u_2 \text{ in m.p.d.}; \tag{19}$$

(ii) for analysis, demanding a curve passing through the origin, the power of the wind velocity is much nearer $\frac{1}{2}$ than $\frac{3}{4}$; (iii) if the form of equation (6a) is to be maintained, the constant is to be reduced from 0·033 to about 0·020, a result that may be due to inaccurate assumptions about the distance away of the hypothetical 'leading edge', may be due to the departure from zero temperature gradient, or may be due to an inaccurate value of α in specifying the shape of the hydro-lapse.

(b) *Open water: energy balance*

The initial objective in this approach was an application to extended periods in which the assumptions made in reducing (8) to (9) would be reasonable; the main discussion will be of this aspect and appears below, but in view of its success it seemed worth while extending the application to individual days. An estimate of E_{MO}, based on energy, was obtained for most days between mid-June and the end of September 1945 and results are shown in figure 5 and table 5. The latter includes a representative sample of the data of the figure, the choice being made at roughly 6-day intervals with an attempt to give reasonable ranges of wind velocities and sunshine conditions, and affords a comparison of the estimates based on energy balance and sink strength (equation 19) with each other and with the observed values of daily evaporation. The values of $(e_s - e_d)$ range from 1·10 to 7·40 mm., those of σT^4 from 13·6 to 14·8, those of $(0{\cdot}56 - 0{\cdot}092\sqrt{e_d})$ from 0·30 to 0·26, the product of the last two functions tending to be constant, and those of $(0{\cdot}10 + 0{\cdot}90n/N)$ from 0·10 to 0·70. From the last, it will be seen that the most important term in the back radiation is the cloudiness factor—the least certain of any. Although they could be deduced from other columns, values of β are given. The figure is extremely encouraging. With the table it shows that the energy balance estimate is too big in mid-summer but improves later in the year. The change in the reflexion coefficient (here taken as constant throughout) would act in the opposite sense, and apart from

* Wing-Cdr Frost, in a private communication, has stated that observations at Poona, India, which were reduced to the form $E/\Delta e = au^{0{\cdot}38}$ by the experimenters can be equally well fitted by

$$E = 0{\cdot}40(1+7{\cdot}3\times10^{-3}u_2)\,(e_s-e_d)\ \text{mm./day}.$$

This is almost indistinguishable from the Rohwer equation.

any deficiencies in (13) itself it is probable that the main cause of the over-estimate is the warming of the bottom of the tank to a higher temperature than the outside soil so producing a positive value of the factor C in (8). The neglect of C in (9), therefore, leads to an over-estimate of H and hence of E.

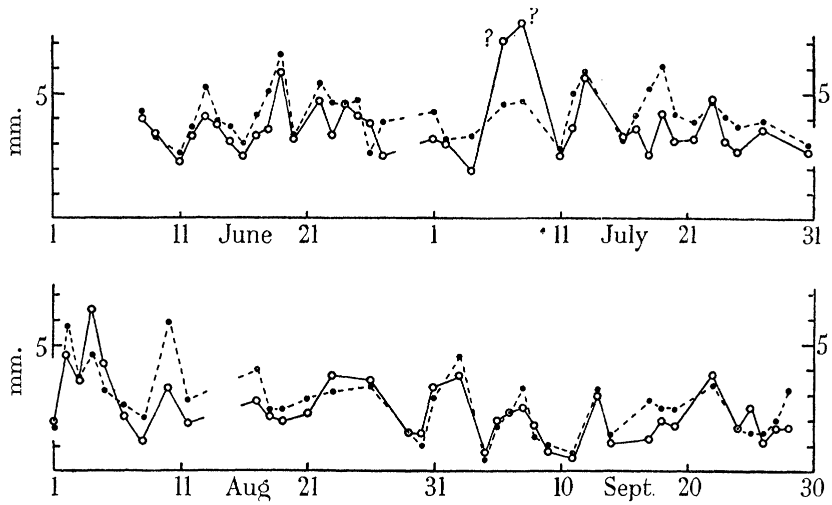

FIGURE 5. Comparison of the observed daily evaporation from open water (tank MO) and estimates based on the energy balance. —○— observed; --●-- energy balance estimate. Year 1945.

TABLE 5. ENERGY BALANCE ESTIMATE FOR TANK MO FOR INDIVIDUAL DAYS, COMPARED WITH THE OBSERVED VALUE AND THE SINK STRENGTH ESTIMATE (EQUATION 19)

					evaporation (mm./day)		
					estimates		observed
date 1945	u_2 (m.p.d.)	$0{\cdot}95R_c$ (mm./day)	H (mm./day)	β	$H/(1+\beta)$	$\Delta ef(u)$	E_{MO}
June 11	149	4·36	3·64	0·37	2·6	2·4	2·3
16	80	5·62	4·52	0·48	3·0	2·7	2·5
22	92	8·28	5·58	0·03	5·4	4·2	4·7
27	118	7·19	4·82	0·35	3·9	4·1	2·5
July 1	197	7·16	5·01	0·16	4·3	4·7	3·2
8	96	8·49	5·98	0·28	4·7	4·8	7·8?
12	50	8·19	5·80	0·15	5·0	3·1	3·6
17	111	6·45	4·78	0·15	4·2	3·2	3·6
23	128	9·09	5·76	0·23	4·7	5·7	4·8
30–31	129	3·72	2·78	−0·07	3·0	2·6	2·7
Aug. 3	67	7·58	4·11	0·12	3·6	4·3	3·6
8	80	3·65	2·67	0·25	2·1	1·4	1·2
17	122	5·65	3·76	−0·07	4·0	2·8	2·8
23	182	5·00	3·43	0·06	3·2	3·2	3·8
26	63	7·23	3·90	0·17	3·4	3·4	3·6
Sept. 2	196	5·40	3·70	−0·18	4·5	3·3	3·8
8	128	1·90	1·53	0·15	1·3	1·4	1·8
9	50	1·43	1·07	0·04	1·0	0·8	0·8
14	133	1·72	1·36	−0·02	1·4	0·9	1·1
22	169	4·52	2·34	−0·31	3·4	2·3	3·8
27	146	3·17	1·63	−0·17	2·0	2·3	1·7

From the table the sink strength estimates based on the fitted curve appear to be a little better than the energy balance estimates. The correlation coefficients between observed and estimated values are about 0·80 in each case, and when it is remembered that the fitting has reduced the sink strength estimate to about 60 % of its theoretical value it is apparent that on the basis of the original predictions the energy balance estimate is the better. The two estimates agree on 8 July when the observed value was extremely high and was queried at the time of observation. In open country there are several causes of spurious high readings; rabbits and birds appreciate an open pool on a hot day and although the enclosure was refitted with wire netting for this experiment it is impracticable to take measures to ensure 100 % freedom from intrusion. Leaks are usually unidirectional and although a big leak is easily noticed, a small one, particularly if variable, could easily be overlooked. Replication is the only safe control here, and the close agreement of the sink strength results for cylinder O and tank MO is regarded as confirmation of the general water-tightness of both containers.

(c) *Evaporation on individual days* (*other surfaces*)

No detailed analysis has been attempted, for two reasons. With water-tables at some distance below the surface there is always some drying out of the soil above the water-table that does not affect the water-table, so that on rain-free days the movement of the water-table does not represent all the evaporation taking place. On a rain day, no rise in water-table will occur until this accumulated deficit of moisture has been made up and on such days the estimate of evaporation based on water-table movement and rainfall will be excessive.

The second reason is that changes in soil temperature from day to day produce changes in the surface tension of the water held in the soil above the water-table and slight water movements take place accordingly. During dry periods the movements of the water-table in cylinder 24 B were due almost entirely to temperature changes, and evaporation was negligible by comparison.

Over an extended period the effect of temperature changes under the saturated surfaces is negligible; if the period is chosen so that its beginning and end are marked by a rise in water-table due to rain then one can be sure that the soil moisture content above the water-table is the same at beginning and end, and (18) can be applied with confidence. Such periods have been termed 'natural periods' (Penman & Schofield 1941) and are the basis of the ensuing discussion.

5. Evaporation in natural periods

(a) *General*

The main discussion will be confined to the open water surfaces, the bare soil with water-table at 5 in. and the turf with water-table at 16 in., but it will be useful to give a brief account of the performance of other cylinders. The bare soil cylinders with water-tables at 10, 16 and 24 in. failed to satisfy the condition of continuous saturation at the surface; the first showed signs of drying during extended periods of rainfree weather and the other two were almost continuously dry except for a day or two after rain. Under turf, the water-table at 10 in. was probably too high for the proper development of the plant, and both growth and transpiration were slightly less than for cylinder 16T; the 1945 results showed transpiration to be about the same for cylinders 16T and 24T, although the crop yield was greater on the latter; the turf over the deepest water-table (cylinder 36T) failed to establish itself with the same luxuriance as the others and little of any value has yet emerged from the results.

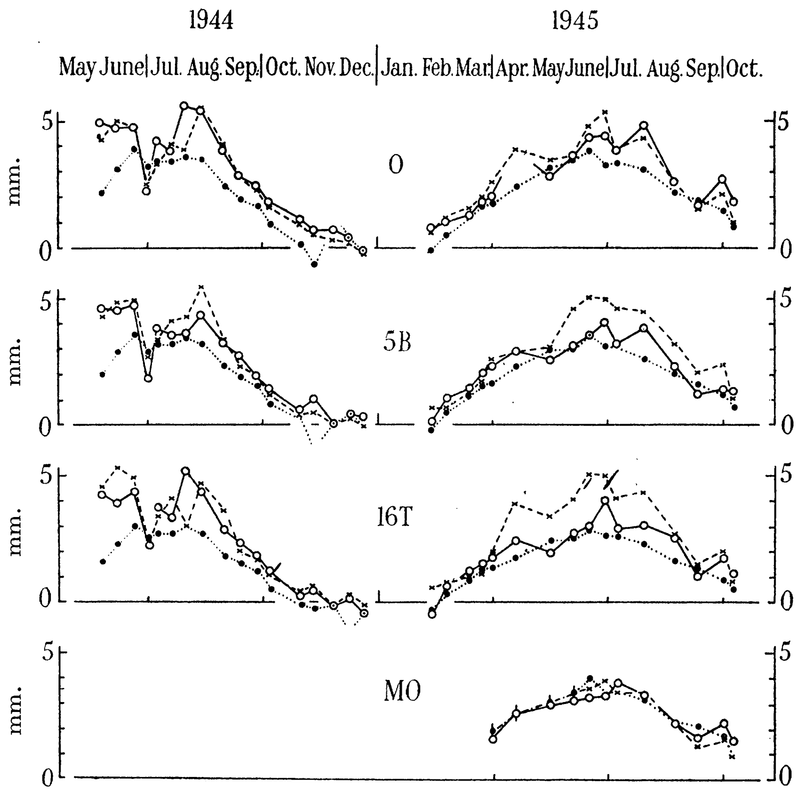

FIGURE 6. Mean daily evaporation in natural periods for surfaces with non-limiting water supply. (Open-water: O and MO. Bare soil with water-table at 5 in.: 5B. Turfed soil with water-table at 16 in.: 16T.) —○— Observed valves. Estimates: --×-- sink strength, ··●·· energy balance and combined.

The results of 18 months for cylinders O, 5B, 16T and tank MO are summarized in figure 6, and with a few supplementary notes the figure should be almost self-explanatory. Apart from the large winter gap, when snow and ice prevented readings from being obtained, there are one or two minor gaps of a few days when records were unobtainable. The lines drawn have no significance other than helping the eye to follow seasonal changes.

The sink strength estimates are based on the mean wind velocity for the period, and the mean values of T_s and T_d from which e_s and e_d were derived. For cylinders O, 5B and 16T the linear expression derived for cylinder O was used (table 4, column 1); for tank MO the corresponding equation (19) was used.

The radiation estimates are based on (13) and (9), using reflexion coefficients of 0·05, 0·10 and 0·20 for open water, bare soil and turf respectively; for cylinder O and tank MO, therefore, the value of H was the same, but the values of β were not necessarily the same, depending upon the values of the surface temperatures.

As the surface temperature of tank MO was not measured until mid-June 1945, the combined estimate (equation 16) was made for the preceding natural periods.

(b) *Comments and conclusions*

(i) For cylinder O the sink strength estimate is a reasonably good fit throughout, suggesting that in selecting results for figure 2 there has been no undue bias.

(ii) For cylinders 5B and 16T the sink strength estimate is good in 1944 but too big in 1945. It is difficult to interpret the turf results as the thermometer bulb was usually covered by growing grass of varying length; perhaps one ought to be surprised at such an exposure combined with a formula based on open water leading to results so near observation. In the case of the bare soil, a reasonable explanation is available. During the summers, and particularly in 1945, a tough wiry weed established itself on the surface and by its mere physical presence probably slowed up evaporation by decreasing wind speed over the surface. As a result of this a little more heat would be available for warming the surface, i.e. T_s, and hence e_s and $(e_s - e_d)$, would increase, so leading to an increased estimate as a result of a decreased observed evaporation.

(iii) For cylinders O, 5B and 16T the radiation estimates are almost invariably too low. In some of the winter periods the value of β reached very uncertain values near -1 and the derived values of $H/(1+\beta)$ were absurd. These values are not plotted.

(iv) For tank MO both estimates are reasonably good and table 5 and figure 5 above may be regarded as giving the fine structure of some of the results shown in figure 6.

(v) Comparison of the results for cylinder O and tank MO so far quoted seem, superficially, to be in conflict; the same sink strength formula fits both whereas the radiation estimates fit the tank results only. The evaporation from the tank was usually about 25 % less than that from the cylinder (table 6 below), but the surface temperature was correspondingly lower, leading to the near agreement of table 5. It is suggested that the increased evaporation from cylinder O was due to the greater surface temperature, i.e. to an extra supply of energy being available to it that was not available for the tank, and that the exclusion of this additional energy supply from the energy balance for cylinder O led to the noted underestimates of evaporation on this basis. Whereas tank MO had an all-soil surround, O and the other cylinders had a hollow on one side. The air in this would warm up during the day to temperatures much in excess of the soil or water in the cylinders at the same depth, leading to an inflow of heat, i.e. to a negative value of C in (8), at least for midsummer months.

It is reasonable to assume that the effect would be the same order for all cylinders, i.e. that *relative* values of evaporation from the three kinds of saturated surfaces would not be materially affected and that one of the major aims of the experiment has not been upset by the deficiency of the experimental site.

6. Conclusions from results of preceding paragraphs

It is convenient to interpolate a short set of conclusions based on the study of daily and periodic evaporation. Without repeating the reservations already made concerning experimental accuracy and theoretical adequacy, we have:

(*a*) A sink strength formula has been obtained that agrees closely with the results of intensive work by Rohwer, and is substantially the same for two open water surfaces having different environments.

(*b*) An energy balance has led to close agreement with observed values for one of these surfaces in which the conditions most nearly satisfy the basic assumptions made in striking the balance.

(*c*) The discrepancy for the other surface is of a kind that can reasonably be applicable to all the cylinders similarly exposed, so that relative values of evaporation rates may be deduced.

7. Results (continued): relative evaporation rates

Table 6 shows the seasonal variation in evaporation from cylinder O, expressed in *in./day*, and the relative rates for bare and turfed soil, the natural periods being grouped roughly in calendar months. For 1945 the mean daily rates for tank MO are included. The bare soil cylinder was set up for a new experiment in December 1945 involving destruction of the surface.

Natural surfaces that are bare, such as arable land before a crop is established, will rarely remain moist in summer when weeds can grow, and will, under ordinary cultivation, rarely grow weeds in winter when the soil will remain moist. It is, therefore, permissible to select results from the preceding table and to state that the evaporation rate from a freshly wetted bare soil will be about 90% of that from an open water surface exposed to the same weather. This is in agreement with the results of indoor experiments (Penman 1941) and other outdoor work (e.g. White 1932).

It is not so easy to reach a firm decision about the grass surface. Assuming, for simplicity, that the leaf temperature is always the same as that of the open water surface, the ratio E_T/E_0 will depend upon the length of daylight (N hr.), and the difference between the minimum surface temperature and the dewpoint. If this difference is large compared with the diurnal temperature change, the value of E_T/E_0 will be of the order of $N/24$, i.e. will range from about 0·70 in summer, to about 0·30 in winter at Rothamsted. As the excess of minimum over dewpoint temperature decreases, both these extreme ratios increase, and when the difference is zero they will be of the order 0·95 and 0·58 respectively, with a value of about 0·83 at the equinoxes (assuming a sinusoidal variation of diurnal temperature change). When the dewpoint temperature is greater than the surface minimum, conditions are more complicated, as condensation will take place on both kinds of surface, and until the dew is evaporated both will behave as open water surfaces whatever the light conditions. Under these conditions the relative evaporations over a whole day will approach equality, although the absolute amounts will tend to be small.

TABLE 6. SEASONAL VARIATION IN RELATIVE EVAPORATION

period 1944	E_0 (in./day)	E_B/E_0	E_T/E_0	period 1945	E_0 (in./day)	E_B/E_0	E_T/E_0	E_{MO} (in./day)
Feb.	—	—	—	8 Feb.–4 Mar.	0·04	0·78	0·31	—
Mar.	—	—	—	5 Mar.–7 April	0·06	1·10	0·86	0·06
April	—	–	—	8–30 April	0·10?	1·05?	0·92?	0·10
9 May–1 June	0·18	0·91	0·83	4–25 May; 28 May–9 June	0·11	0·89	0·69	0·11
2–28 June	0·19	0·98	0·88	10–22 June; 23 June–2 July	0·16	0·83	0·72	0·12
29 June–4 Aug.	0·16	0·82	0·89	3–12 July; 16 July–8 Aug.	0·17	0·84	0·71	0·14
5 Aug.–2 Sept.	0·19	0·81	0·78	12 Aug.–2 Sept.	0·11	0·87	0·96	0·08
5–30 Sept.	0·10	0·91	0·79	6–15 Sept.; 16–24 Sept.	0·09	0·61	0·61	0·07
1–10 Oct.	0·05	0·65	0·48	25 Sept.–22 Oct.	0·07	0·70	0·64	0·06
20 Oct.–6 Nov.								
7–13 Nov.	0·03	0·54	0·0	1–28 Nov.	0·03	0·7?	0·6	0·02
20–30 Nov.								
1–22 Dec.	0·01	0·8	−0·4	29 Nov.–22 Dec.	0·05	—	−0·0	0·05

The simple initial assumption is not likely to be realized in practice, and both mean surface temperature and its daily amplitude will be important. In winter, when the important temperature differences are likely to be small and unequal there may be more condensation on one surface than another and so negative ratios might be obtained (December 1944 and 1945).

It is clear that a more detailed study of this part of the problem is needed, and at the moment only a limited generalization can be made with the reservation that it may apply to the Rothamsted site and the years 1944–45 only. Using the *totals*, for midsummer periods (May–August inclusive) the ratio is 0·81; for equinoctial periods (March–April, September–October) it is 0·72; for midwinter the results are too few and too erratic to attempt expression of a ratio. We can, however, get an indication of the order of magnitude from another source. At Fleam Dyke, Cambridge, two drain gauges, one bare and the other turfed, are maintained side by side. Over winter months, when the summer drying has been made good in both gauges, E_B is greater than E_T. For the months December–March inclusive, in the years 1939–40 to 1942–43, the totals were:

$$\Sigma E_B = 10{\cdot}5\,\text{in.},\quad \Sigma E_T = 7{\cdot}6\,\text{in.}\quad \text{i.e.}\quad E_T/E_B = 0{\cdot}725$$

(data kindly supplied by Mr Porteous, Engineer-in-charge, Cambridge University and Town Waterworks Co.). Putting $E_B/E_T = 0{\cdot}90$, then $E_T/E_0 = 0{\cdot}65$, and as the March transpiration would be greater than that in November, the midwinter ratio would be smaller. To a satisfactory degree of accuracy it may be rounded off to 0·60.

8. Conclusions from results of seasonal variation in relative evaporation

(*a*) The evaporation rate from continuously wet bare soil is 0·9 times that from an open water surface exposed to the same weather conditions in all seasons.

(*b*) The corresponding relative evaporation rate from turf with a plentiful water supply varies with season of the year. Provisional values of E_T/E_0 for southern England are:

Midwinter (November–February)	0·6
Spring and autumn (March–April, September–October)	0·7
Midsummer (May–August)	0·8
Whole year	0·75

(*c*) The discrepancy between cylinder O and tank MO is greatest in midsummer when the effect of extra heat flow through the walls of cylinder O is likely to be most important.

9. Tests on other data

(*a*) *Data required and methods of using them*

Before the conclusions of § 8 can be applied to soil surfaces it is necessary to estimate the evaporation that would take place from an open water surface exposed to the same weather. To avoid reference back, the requirements are repeated: (i) for the sink strength estimate it is necessary to know the mean surface temperature, the mean dewpoint temperature and the mean wind velocity. Then

$$E_0 = 0{\cdot}35(1+9{\cdot}8\times10^{-3}u_2)(e_s-e_d) \text{ mm./day;} \tag{19}$$

(ii) for the energy balance estimate the requirements are: mean daily short-wave radiation (or mean daily duration of sunshine), mean daily cloudiness (or mean daily duration of sunshine), mean air temperature, mean dewpoint temperature, and mean surface temperature. Then

$$E_0 = H/(1+\beta) \text{ mm./day,} \tag{11}$$

where
$$\left.\begin{aligned} H &= R_C(1-r)-\sigma T_a^4(0{\cdot}56-0{\cdot}092\sqrt{e_d})(0{\cdot}10+0{\cdot}90n/N)\\ \text{and}\quad R_C &\doteqdot R_A(0{\cdot}18+0{\cdot}55n/N);\end{aligned}\right\} \tag{13}$$

(iii) for the combined estimate there must be known, mean air temperature, mean dewpoint temperature, mean wind velocity, and mean daily duration of sunshine. Then

$$E_0 = (H\Delta+0{\cdot}27E_a)/(\Delta+0{\cdot}27) \text{ mm./day,} \tag{16}$$

where H is given by (13) above, and

$$E_a = 0{\cdot}35(1+9{\cdot}8\times10^{-3}u_2)(e_a-e_d) \quad \text{(cf. (19))}.$$

The values of N and R_A will vary with latitude and season, but are readily obtainable from standard sources. The value of r has a similar double variance but it will probably be sufficiently accurate to use a constant value of 0·05.

For general use, where E_0 has not been directly measured, the third method is most useful, and as the dependence on wind speed is not very critical, a Beaufort wind force can be substituted for u_2 so giving an opportunity of making an evaporation estimate from the data of a weather map. To convert the sink strength formula it is sufficient to use the 'good' expression for cylinder O (table 4) combined with two standard conversion factors:

$$E_0 = 0{\cdot}033u_2^{0{\cdot}68}(e_s-e_d), \quad u_2 \text{ in miles/day;}$$

$$u_2 = 0{\cdot}78u_{10};$$

$$u_{10} = 1{\cdot}87B^{\frac{3}{2}}\times24, \quad u_{10} \text{ in miles/day;}$$

i.e.

$$E_0 = 0{\cdot}033[0{\cdot}78\times24\times1{\cdot}87B^{\frac{3}{2}}]^{0{\cdot}68}(e_s-e_d);$$

$$= 0{\cdot}37B^{1{\cdot}02}(e_s-e_d) \text{ mm./day.}$$

The coarseness of the Beaufort estimates of wind force suggests that this may safely be reduced to

$$E_0 = 0{\cdot}37B(e_s-e_d) \text{ mm./day,} \tag{20}$$

giving

$$E_a = 0{\cdot}37B(e_a-e_d) \text{ mm./day}$$

for use in (16).

Although evaporation data exist for many sites over long periods of time there are not many sets that have sufficient contemporary meteorological data alongside to enable a comparison of observed and predicted evaporation to be made. The few cases discussed below have been chosen to give a fairly wide variety of sites and types of surface.

(b) *Open water*

(i) Fitzgerald (1886). Pans were floated in the middle of an 85 acre reservoir at *Chestnut Hill, Boston, Mass.* Table 7 gives results for a pan 10 ft. diameter and 10 ft. deep, filled to within 3 in., and sunk to within 6 in. of the top. The anemometer was at 30·5 ft. above the surface. Values of E_0, u, T_s, T_a and h were measured on 8 days between June and October 1885. Using (19) the following results are obtained, E_{19} representing the estimates.

TABLE 7. DAILY EVAPORATION AT BOSTON, U.S.A.

day ...	1	2	3	4	5	6	7	8
u_2 (m.p.d.)	223	135	116	150	127	75	51	129
(e_s-e_d) (mm.)	10·4	7·6	7·8	7·7	10·0	8·0	6·3	2·5
E_{19} (mm./day)	11·6	6·2	5·8	6·7	7·8	4·9	3·3	2·0
E_0 (mm./day)	10·7	6·8	6·1	6·6	7·1	7·1	4·1	2·5

(ii) Visentini (1936). A pan was floated in the reservoir at *Molato, Italy*, with an anemometer on the dam. Values of T_s, T_a, u and h are given. In the absence of information it is assumed that the anemometer height was 2 m. and the calibration the same as for the Rothamsted anemometer.

TABLE 8. MEAN DAILY EVAPORATION AT MOLATO, ITALY

1934 ...	Aug.	Sept.	Oct.	Nov.	Dec.
u (m.p.d.)	67	48	44	82	77
$(e_s - e_d)$ (mm.)	8·2	6·85	5·8	3·2	1·95
E_{19} (mm./day)	4·8	3·5	2·9	2·1	1·2
E_0 (mm./day)	5·1	3·9	4·1	2·3	1·3

1935 ...	Mar.	Apr.	May	June	July	Aug.	Sept.
u (m.p.d.)	106	96	99	87	91	70	72
$(e_s - e_d)$ (mm.)	3·0	5·25	3·9	8·2	8·5	6·3	5·4
E_{19} (mm./day)	2·1	3·6	2·7	5·4	5·7	3·9	3·3
E_0 (mm./day)	1·8	2·7	3·0	6·2	7·9	5·7	4·3

(iii) Davydov (1936). Measurements were made on *Sevan Lake, Soviet Armenia* (no details). Values of $(e_s - e_d)$ between lake surface and 10 cm. above, and of wind velocity at 9 m. are given. Results are means for 1927–30:

TABLE 9. MEAN DAILY EVAPORATION AT SEVAN LAKE, SOVIET ARMENIA

	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
u_2 (m.p.d.)	136	106	123	157	119	144	140	153	183
$(e_s - e_d)$ (mm.)	0·1	0·0	1·5	2·3	3·9	4·7	4·9	3·8	3·3
E_{19} (mm./day)	0·1	0·0	1·2	2·0	3·0	4·0	4·1	3·3	3·2
E_0 (mm./day)	0·4	0·2	1·2	2·1	3·4	4·5	4·1	3·6	2·9

(iv) Ray (1931). Monthly means for a standard U.S. Weather Bureau evaporation pan are given for 1917–30 for *San Juan, Puerto Rico*, together with u_0, T_a, mean saturation deficit and mean hours of sunshine. For speed of computation a 12 hr. day has been assumed for the whole year. As results are given in in./month and $(e_a - e_d)$ in inches of mercury, the same form is kept in table 10:

TABLE 10. MEAN MONTHLY EVAPORATION AT SAN JUAN, PUERTO RICO

	Jan.	Feb.	Mar.	Apr.	May	June
E_a (in./month)	5·35	4·75	7·3	7·2	7·6	7·4
H (in./month)	3·8	5·15	6·1	7·0	7·05	7·7
E_{16} (in./month)	4·25	5·05	6·4	7·05	7·2	7·65
E_0 (in./month)	5·55	5·55	7·6	7·85	7·75	7·45

	July	Aug.	Sept.	Oct.	Nov.	Dec.
E_a (in./month)	8·55	8·15	6·05	5·0	4·8	5·75
H (in./month)	7·1	7·55	6·4	5·3	4·3	3·8
E_{16} (in./month)	7·55	7·7	7·3	5·2	4·45	4·3
E_0 (in./month)	8·15	8·05	6·6	5·85	5·1	5·45

(c) *Bare soil*

There are few records available and information about related weather is even more rare. By the courtesy of the Indian authorities, the rainfall, drainage and other weather records for Pusa have been made available from 1907 to 1934. Pusa lies in the monsoon region of Asia, at latitude 26° N. in the Ganges basin, and in most years it is a fairly reasonable assumption that once the monsoon has broken, bare soil will remain moist for most of the monsoon period.

In 1906 four drain gauges were constructed, each 1/1000 acre in area, without disturbing the soil, two being 3 ft. deep and two 6 ft. deep. One at each depth was kept bare and the other pair cropped, and daily records of rainfall and drainage for months in which at least one gauge ran are available from 1907–34. The crop carried by gauges II (6 ft.) and IV (3 ft.) during the monsoon period was either maize (1907–15) or sunn hemp (1916–34), sowing taking place in June each year. Both are tall plants (8 ft. and 6 ft. high), and, standing well above the turf surround, they would be better ventilated, intercept more radiation and expose a larger transpiring surface to the air than a patch of the same size in the middle of a large field. Transpiration would be abnormally great, and the evidence of the cropped gauges is to be rejected on the ground that the same surface was not typical of its environment.

The records were separated into natural periods in which the difference between rainfall and drainage (or drainage and run-off) can be equated to the evaporation of the period. As drainage continued for several days after rain it was not always possible to decide which was the last rainfall causing drainage, and there are inevitable uncertainties in the estimation of $(R-D)$ per day as a result. As elsewhere, all estimates of evaporation are very much dependent upon the drain gauge receiving the same amount of rain as the rain gauge.

The values of $R-D$ for gauges I and II (6 ft. and 3 ft. bare) usually agreed closely and there was general consistency in the performance of gauges II and IV. A condensed summary for 2 years shows the order of evaporation per day from all four; further analysis will be restricted to the records for gauge I.

TABLE 11. COMPARATIVE EVAPORATION AT PUSA

period	R/day (in.)	$(R-D)$/day (in.) I (6′B)	II (6′C)	III (3′B)	IV (3′C)
1911					
8–18 July	0·34	0·17	0·24	0·15	0·23
19 July–25 Aug.	0·47	0·16	0·37	0·15	0·35
26 Aug.–26 Sept.	0·27	0·12	0·24	0·12	$>0·27$
27 Sept.–13 Oct.	0·22	0·12	0·11	0·10	no D
1922					
2–26 July	0·72	0·11	0·22	0·08	0·13
27 July–9 Aug.	0·53	0·09	0·21	0·05	?
10–20 Aug.	0·24	0·12	0·20	0·10	?
21 Aug.–23 Sept.	0·21	0·09	0·22	0·06	0·19
29 Sept.–5 Oct.	0·19	0·13	0·19	0·14	$>0·19$

Weather observations at Pusa (1911–33) were made at 08.00 hr. and included dry and wet bulb temperatures, air maximum and minimum temperatures, anemometer readings at 08.00 and 08.03 hr., cloud amount, and 'instrumental test observations', the last being the actual readings of the three dry thermometers, presumably expected to be equal when read. These readings never agreed and differences were erratic, ranging up to 3° F, the usual order being dry > max. > min.

Assuming that the anemometer ran continuously between 08.03 hr. one day and 08.00 hr. the next, the run-of-the-wind per day was obtained for all days except when the reading passed through an unknown zero; the height is assumed to be 2 m. and the calibration the same as the Rothamsted instrument (table 2 above). From the mean air temperature and the 08.00 hr. value of dewpoint the value of the mean saturation deficit was obtained. From these, values of E_a were obtained.

The determination of H had to be based on a single cloud estimate per day; comment is unnecessary. There seemed little point in evaluating it for all periods in all years and only two, 1911 and 1922, are considered in detail (table 12). Mean wind speeds (as measured) ranged from 33 to 133 miles/day, mean and 08.00 hr. air temperatures from 81 to 86° F, 08.00 hr. humidity from 87 to 92 % and estimated n/N from 0·00 to 0·64.

(*d*) *Cropped soil*

Using the annual summary of the Monthly Weather Report, data for 70 stations in the British Isles have been abstracted for the years 1930–39 and long period means obtained for mean air temperature, mean vapour pressure, mean Beaufort wind force and the mean ratios of actual/possible hours of sunshine. From these, values of E_a and H were obtained for each site and values of E_0 derived, using equation (16). Converted to inches per year, an evaporation map of the British Isles was obtained

TABLE 12. ESTIMATED E_B AND MEASURED $(R-D)$/DAY FOR BARE SOIL: PUSA 1911 AND 1922

period	R/day (in.)	E_a/day (in.)	H/day (in.)	E_{16} (in./day)	$0·9E_{16}$ (in.)	$(R-D)$/day (in.)
1911						
8–18 July	0·34	0·08	0·11	0·10	0·09	0·17
19 July–29 Aug.	0·46	0·11	0·16	0·15	0·13	0·16
30 Aug.–8 Sept.	0·17	0·17	0·13	0·14	0·13	0·11
9–26 Sept.	0·32	0·08	0·16	0·14	0·12	0·14
27–30 Sept.	0·18	0·07	0·11	0·10	0·09	0·14
1–13 Oct.	0·22	0·09	0·14	0·13	0·11	0·10
1922						
2–20 July	0·80	0·09	0·12	0·11	0·10	0·10
21–26 July	0·45	0·12	0·12	0·12	0·11	0·15
27 July–9 Aug.	0·54	0·12	0·14	0·13	0·12	0·09
10–15 Aug.	0·12	0·04	0·08	0·07	0·06	0·08
16–20 Aug.	0·38	0·12	0·17	0·16	0·14	0·18
21–26 Aug.	0·16	0·07	0·12	0·11	0·10	0·10
27–30 Aug.	0·25	0·09	0·10	0·10	0·09	0·16
31 Aug.–5 Sept.	0·25	0·08	0·12	0·11	0·10	0·13
6–10 Sept.	0·15	0·09	0·22	0·18	0·17	0·13
11–28 Sept.	0·34	0·09	0·14	0·13	0·11	0·14
29 Sept.–5 Oct.	0·19	0·02	0·19	0·14	0·13	0·14

showing the probable value of annual evaporation from open water in exposed sites. From the conclusions in § 8 above one would expect the corresponding value of the annual evaporation from cropped land to be $\frac{3}{4}$ of E_0 if the crops transpired at maximum rates all the year; in practice the rates will be less than this because of the ripening process in annual vegetation and/or the lack of summer rainfall, particularly in south-east England, but in the table below this conversion factor is applied uniformly. The table shows the observed difference between rainfall and runoff for certain catchment areas (Lloyd 1940, 1941, 1942) (these are rather monotonous), the observed difference multiplied by $\frac{4}{3}$, which should be the expected corresponding open water evaporation, and the estimated value of E_0 based on annual mean values of weather elements for stations somewhere near, if not in, the catchment area.

Table 13. Evaporation from catchment areas

catchment	period	mean rainfall-runoff (in./year)	$4/3(R-r)$	estimated E_0 for nearby sites (in./year)
Lea	1928–36	19·2	26	Greenwich, 25 Rothamsted, 20
Thames	1928–36	18·7	25	Kew, 26 Oxford, 24
Severn	1928–36	18·8	25	Ross-on-Wye, 24 Cheltenham, 21 Shrewsbury, 21
Vrnwy	1932–38	19·1	26	Shrewsbury, 21 Sealand, 24 Llandudno, 23
Rivington	1932–38	17·4	23	Stonyhurst, 21 Hutton, 18
Spey	1936	10·3	14	Dalwhinnie, 17

Detailed examination of Rothamsted data has shown that the sum of the twelve monthly estimates exceeds the annual estimate by about 10 %, due to the extra weight which should be given to summer evaporation. A similar increase is to be expected for other sites and should be borne in mind in reading table 13.

10. General conclusion

A detailed discussion of the data presented in § 9 (*b*), (*c*) and (*d*) would be intolerably long, and much of it would be concerned with the adequacy of the observations rather than the adequacy of the equations on which the estimates are based. The general impression is satisfactory for all three types of surface, and the wide range of climatic regions employed indicates that something of universal significance has been obtained in the results of §§ 3 to 8, although there must inevitably be something of the time and place at which the experimental work was done included in the equations.

Two aspects of evaporation have been under review. There is that of the physicist and mathematician seeking facts to fit a formula; sufficient has emerged to show possible sources of weakness in the theoretical treatment of both sink strength and energy balance and to show the relative importance of the quantities that must be measured to obtain adequate accuracy in experimental trials. There is also that of the 'practical' man—water engineer or meteorologist—seeking a formula to fit the facts. Formulae have been given and where all the necessary measurements can be made, or values forecast, then reliable evaporation rates can be estimated or predicted. There are still empirical aspects of both sink strength and energy balance estimates and until these are removed there must always be some doubt about the possibility of successful translation in space or time of the formulae.

The work described in the preceding pages is an extension of research carried out at Rothamsted Experimental Station before 1941. It was resumed in 1944 at the request of the Meteorological Office, and it is a pleasure to be able to record my appreciation of the assistance given by several branches of the Office in the form of equipment, information and advice. I am particularly indebted for many helpful discussions to Mr C. S. Durst of the Meteorological Office, and to my colleague, Dr R. K. Schofield. To the Director of the Meteorological Office and the Meteorological Research Committee I am grateful for the helpful reception given to the report on which this paper is based and for permission to publish it.

Finally, this work could not have been done at short notice if the basic equipment of the enclosure had not been available: to Dr B. A. Keen, F.R.S., until recently Head of the Physics Department at Rothamsted, especially grateful acknowledgement is due for the foresight that provided the installation with full knowledge that it would be many years before the soil would be fit for experimental work.

References

Bowen, I. S. 1926 *Phys. Rev.* **27**, 779.
Brunt, D. 1939 *Physical and dynamical meteorology*. Camb. Univ. Press.
Cummings, N. W. & Richardson, B. 1927 *Phys. Rev.* **30**, 527.
Davydov, V. K. 1936 *Assoc. Intern. D'Hydrologie Sci. Bull.* no. 22, 142.
Fitzgerald, D. 1886 *Trans. Amer. Soc. Civ. Engrs*, **15**, 581.
Geiger, R. 1927 *Das Klima der bodennahen Luftschicht*. Brunswick: F. Vieweg.
Kimball, H. H. 1914 *Mon. Weath. Rev., Wash.* **42**, 474.
Lloyd, D. 1940 *Quart. J.R. Met. Soc.* **66**, 181.
Lloyd, D. 1941 *Quart. J.R. Met. Soc.* **67**, 33.
Lloyd, D. 1942 *Quart. J.R. Met. Soc.* **68**, 35.
Pasquill, F. 1943 *Proc. Roy. Soc.* A, **182**, 75.
Penman, H. L. 1940 *Quart. J.R. Met. Soc.* **66**, 401.
Penman, H. L. 1941 *J. Agric. Sci.* **31**, 454.
Penman, H. L. & Schofield, R. K. 1941 *J. Agric. Sci.* **31**, 74.
Prescott, J. A. 1940 *Trans. Roy. Soc. S. Aust.* **64**, 114.
Ray, C. L. 1931 *Mon. Weath. Rev., Wash.* **59**, 192.
Rohwer, C. 1931 *U.S. Dept. Agric. Tech. Bull.* 271.
Sutton, O. G. 1934 *Proc. Roy. Soc.* A, **146**, 701.
Sutton, W. G. L. 1943 *Proc. Roy. Soc.* A, **182**, 48.
Sverdrup, H. V. 1945 *Oceanography for meteorologists*. London: George Allen and Unwin.
Visentini, M. 1936 See Davydov. Bull. no. 22, p. 119.
White, W. N. 1932 U.S. Dept. Interior. Water Supply Paper 659.