The Physical Bases of Irrigation Control

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PART I. THEORY

1. *Introduction*

The primary purpose of irrigation is to keep the soil wet enough to ensure that water supply is never a limiting factor in crop growth. If it is accepted as axiomatic that maximum growth needs maximum transpiration, then effective physical control of irrigation depends upon the possibility of estimating transpiration rates, and during recent years it has become clear that transpiration rates can be estimated from contemporary weather data. In America, Blaney and his colleagues (1950) and Thornthwaite (1951) have almost reduced weather-based control of irrigation to a routine, but though they differ in the degree of empiricism their emphasis is primarily on relations rather than on reasons. At Rothamsted we have tried to work forward from reasons to relations, using empirical constants only where ignorance makes them unavoidable. Progress has been sufficient to justify field experiments (Penman, 1949, 1952), but only by using an empirical constant (relating transpiration to evaporation from an open water surface) that could not be expected to be valid in a different climate. An attempt to give a theoretical basis for this constant was partly successful (Penman and Schofield, 1951), but only where rather difficult measurements of surface temperature could be made.

The main purpose of the present paper is to attempt a general treatment that avoids this limitation, and to test it in the climate of southern Australia and under the more complex conditions of orchard irrigation. The formal mathematics is given in an appendix.

2. *The Physics of Evaporation*

There are two basic principles in the physics of evaporation. First, the transfer of water to the atmosphere involves a change of state from liquid to vapour, and this demands energy to supply the necessary heat of vaporization: the amount of evaporation is limited by available energy. Second, continued uptake of vapour by the atmosphere requires the air to be less than completely saturated and requires a transport mechanism to move the vapour from moister to drier levels in the atmosphere: the rate of evaporation is controlled by a vapour pressure gradient and a coefficient of turbulent diffusion.

The second principle can be made self-sufficient in estimating evaporation rates from any kind of surface. As examples, Pasquill (1950) has improved a technique first used by Thornthwaite and Holzmann (1939) and brought it to a high degree of precision that will give hour to hour changes in evaporation rates; and Swinbank (1951) has introduced a more fundamental method that will give even higher precision in estimating minute to minute changes. These necessary probings into the fundamental physics of evaporation are essentially research techniques giving fine detail, and for general use something broader and more easily handled is needed. By accepting a small sacrifice in precision this breadth is attainable without sacrifice of principle, but

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it demands some knowledge of the properties of the surface from which the evaporation is taking place, properties that are difficult to measure and could never be measured as routine. They are easiest for an open water surface, from which the rate of evaporation is proportional to the difference between the surface water vapour pressure and the atmospheric water vapour pressure. The factor of proportionality depends in a complex way on wind structure, temperature gradient and roughness of the surface, but by accepting the first sacrifice in precision it is possible to express it simply, as a function of wind speed measured at a standard height. From experiments (Penman, 1948), over the range of wind speeds of practical importance, the working equation for evaporation from open water is

$$E_o = 0{\cdot}35\ (e_s - e_d)\ (1 + u_2/100)\ \text{mm./day}, \qquad (1)$$

where e_s and e_d are the vapour pressures at the surface and in the air, in mm. Hg., and u_2 is the wind speed at 2 metres above the surface, in miles per day. If the value of e_s for a crop could be measured a similar equation would give the transpiration rate.

The first principle is not completely self-sufficient, hence the reversed order in discussion. It involves measurement or estimation of all the ways in which solar radiation is used, leaving heat of evaporation as the only unknown. Ignoring minor terms in the balance sheet, part of the incident radiant energy is reflected, the amount depending on the colour and nature of the surface, and part goes back as an unceasing net outflow of long-wave radiation. The residue retained at or near the surface is known as the 'heat budget', and effectively is shared between energy of evaporation and heating of the air. The heat budget, as income, can be written as

$$H = R_c\ (1 - r) - R_B \qquad (2)$$

where R_c is incoming short-wave energy, completely independent of the surface it reaches, r is the reflection factor, entirely dependent on the surface, and R_B is the net back radiation, dependent on air temperature, atmospheric humidity and cloudiness, and almost completely independent of the surface. Apart from differences in reflection factor, the heat budget at a given place and over a given period will be independent of the surface, i.e. will be effectively the same for all green crops giving a complete ground cover, whatever their shape or height. The heat budget, as expenditure, can be written as

$$H = E + K \qquad (3)$$

where, in consistent units, E is the evaporation and K is the sensible heat transfer to the air. For the pre-supposed condition of non-limiting water supply the heat transfer is only a small fraction of the energy of evaporation, and hence, to a good first approximation, the water consumption of all irrigated crops at a given time and place is effectively the same, and is determined by prevailing weather. Apart from circumstantial confirmation gathered in practical applications (Penman, 1951), this general statement has experimental support from measurements of contemporary transpiration rates of five markedly different kinds of crop, of which Thornthwaite (1951) writes: "Surprisingly, it has been found that the type of vegetation is of relatively minor importance in determining the magnitude of transpiration. The important controls are climatic . . .".

Although of great value as it stands, the statement becomes more valuable when made quantitative. To make it so, it is necessary to separate the two terms in the heat budget, and for this ideas used in the vapour transfer principle are needed. Again, subject to the limitation of a working approximation, it can be stated that the physical mechanism of transfer of heat is the same as that of transfer of vapour, the rate being the product of a temperature difference and a ventilation factor. If the temperature difference is measured between the surface and the air a few feet above, the ventilation

factor is the same as for vapour transfer, i.e. the ratio K/E can be set down using a multiplying constant (γ) to keep units consistent. The formal equation is

$$K/E = \gamma\ (T_s - T_a)/(e_s - e_d) = \beta \quad \text{say}$$

where T_s is the mean surface temperature and T_a is the mean air temperature. From this and equation 3,

$$E = H/(1 + \beta) \qquad (4)$$

Equation 4 can only be used if surface values are known, and here, too, the only relatively easy check is on an open water surface for which e_s is the saturation vapour pressure at T_s.

Two methods of analysis have thus come to the same end-point: evaporation from an open water surface can be estimated from other weather data if the surface temperature is known. The corresponding formal equations must be simultaneously true and so can be solved to eliminate the unknown surface temperature to give an expression for evaporation that does not include surface parameters other than reflection coefficient. As a convenience, the necessary algebra introduces a new term E_a, obtained from equation 1 by replacement of e_s by e_a, where e_a is the saturation vapour pressure at mean air temperature, i.e. the vapour pressure difference factor in E_a is $e_a - e_d$, which is the 'saturation deficit' of the air. The evaporation rate from open water then becomes (Penman, 1948 or 1949)

$$E_o = (\Delta H + \gamma E_a)/(\Delta + \gamma), \qquad (5)$$

where Δ is the slope of the saturation vapour pressure curve at mean air temperature, and is easily found from standard tables.

3. *Application and Extension of Physical Theory*

At this stage four points need mention or discussion:

(a) By making adequate approximations only four weather elements are needed to compute values of E_o, and all are standard—mean air temperature, mean water vapour pressure in the air, mean wind speed, and mean duration of bright sunshine per day (Penman, 1948).

(b) Contemporary measurements of E_o and the transpiration rate from sub-irrigated grass, E_T, gave empirical ratios of E_T/E_o for S.E. England varying from 0·6 in the four mid-winter months to 0·8 in the four mid-summer months (Penman, 1948). These factors have proved to be of adequate accuracy in field experiments on irrigation of sugar beet (Penman, 1949).

(c) An attempt at a theoretical derivation of the conversion factor was successful in giving the right order of magnitude and its seasonal variation (Penman and Schofield, 1951). It was based entirely on the vapour transfer approach, and needed values of surface temperature for both the open water and the transpiring surface.

(d) If to this is added the energy balance concept it ought to be possible to repeat for a short green crop what was achieved for open water, namely to avoid the need for measurement of surface temperature, and hence to estimate from other weather data the rate of transpiration when water supply is non-limiting. The basic principles are the same but are overlain by secondary detail, now to be considered, that could be confusing without the preceding discussion of the application of the principles to open water.

4. *Leaf and Day-length Factors in Transpiration*

The theoretical ratio E_T/E_o is the product of three factors: a vapour pressure factor, a stomatal factor, and a day-length factor. (Appendix, eq. 6.)

The first is simple. If the mean surface temperature of a leaf surface [illegible] from that of an open water surface exposed to the same weather, the [illegible] pressure difference in the transport equation will not be the same for [illegible] surfaces.

The second is more complex. In moving away from an open water surface the vapour encounters resistance at all levels, resistance that is [illegible] calmer the air. For a given wind speed the total resistance between surface and the level at which the vapour pressure is measured is [illegible] constant (a consequence of the first assumption made in this paper). If the transport were by molecular diffusion only this same resistance would be encountered over a very much shorter distance. Though it is [illegible] precise term it is convenient to call this short distance the 'effective length' of the surface, L_a: the effective length offers the same resistance to [illegible] diffusion as the distance between surface and screen height does to [illegible] diffusion, and knowing the coefficient of molecular diffusion of water vapour into air it is easy to convert equation 1 into an expression for effective length as a function of wind speed. (Appendix, para. 12) The value so derived [illegible] be the same for all surfaces having the same aerodynamic roughness. By happy accident the open water and short grass surfaces used in our [illegible] experiments appear to have behaved as though equally rough, and hence values of L_a derived from equation 1 can be used as measures of the effective length of surfaces of grass and other short vegetation. This is a resistance [illegible] the air, and to it must be added a resistance in the leaf. Arising at the [illegible] of the mesophyll tissue lining a sub-stomatal cavity, the vapour has to [illegible] to the inside opening of the stoma, through the epidermis, and then [illegible] from the outside opening before merging with corresponding streams from neighbouring stomata: thereafter the vapour flow encounters the [illegible] resistance already assessed. If the geometry of the stomata is known [illegible] sufficiently simple the stomatal resistance to flow can be computed [illegible] equivalent length L_s, but information is so scanty, and such geometry [illegible] known is so complex, that this method of estimating stomatal resistance [illegible] diffusion is unlikely to be of any general use. An alternative, offering [illegible] promise, is the direct technique used by Heath (1941) and Milthorpe [illegible] preparation) to measure the stomatal conductivity for diffusive flow, [illegible] reciprocal of which is the 'effective length' of the stomatal array. [illegible] it known in some way, then the total effective length for a leafy surface [illegible] L_a+L_s: for an open water surface it is L_a: and the stomatal factor [illegible] is $L_a/(L_a+L_s)=S$, say.

The third factor allows for the normal night closure of the stomata [illegible] becomes simple if the assumptions are accepted. They are: (i) the atmospheric water vapour pressure, e_d, remains constant throughout the day; (ii) the surface vapour pressure goes through a sinusoidal cycle with midnight [illegible] mum and midday maximum; (iii) the stomata are fully open throughout daylight and completely closed in darkness. The day-length factor [illegible] reduces to the sum of two terms, the first being $N/24$ where N is the [illegible] of daylight and so has an annual cycle with an amplitude varying with latitude [illegible] and the second being a sine term that becomes less and less important [illegible] drier the atmosphere. The sum of the two terms is always less than [illegible] Representing the factor by D, the Penman and Schofield equation can [illegible] written

$$\frac{E_T}{E_o}=\frac{e_{sT}-e_d}{e_{so}-e_d}\cdot S\,D \qquad (6)$$

If now equation 1 is re-written as $E_o=f(u)(e_{so}-e_d)$, then

$$E_T=f(u)(e_{sT}-e_d)\,SD, \qquad (7)$$

in which e_{sT} is the saturation vapour pressure at the mean surface temperature over a period of 24 hours.

Calculation of Transpiration Rate

Equation 7 is the first of the pair needed to find E_T. The second comes from the energy balance, and comes simply. As income, H_T differs from H_o only in the reflection factor; as expenditure, the heat budget is again shared between evaporation and sensible heat transfer:

$$H_T=E_T+K_T \qquad (8)$$

Applying the same physical principles and algebra to these equations (Appendix, para. 13), the result is

$$E_T=\frac{\Delta H_T+\gamma E_a}{\Delta+\gamma/SD}, \qquad (9)$$

where Δ, γ, and E_a have their previous meanings.

The new technical problems raised are the estimation of D and S (the more difficult), but it should be noted that both are less than unity, and as H_T is less than H_o, then E_T will always be less than E_o; that is, the rate of transpiration of a short crop cannot exceed the rate of evaporation from an open water surface in the same environment.

Tall Crops and Trees

The result just obtained can be true only for short crops. As the height increases new factors come in that are difficult to assess quantitatively. First, the roughness of the surface is greater, and an increase in evaporation rate is possible; second, swaying of the crop may have the same effect by expediting the transfer of damper air from within the crop to the turbulent region above it; and third, there may be significant movement of air through the crop. For one important type of crop this third factor is sufficiently important to justify an attempt at quantitative discussion.

Orchard trees are usually far enough apart to permit air movement below canopy level, so that the ventilation factor in evaporation may be increased. If the heat budget remains unchanged, any increase in evaporation must be at the expense of the heat transfer to the air, i.e. air temperature in and above an irrigated orchard must be less than over an irrigated pasture. To assess quantities demands even more sweeping assumptions than any previously made.

The normal orderly array of an orchard is such that for almost any direction of view the trees are in straight lines with clear lanes between. It will be assumed (i) that whatever the wind direction it will blow parallel to rows of trees; (ii) that the rows are effectively continuous hedges; and (iii) that the hedges in vertical section have some simple geometrical shape from which the effective area ventilated can be estimated. The resulting increase in evaporation rate cannot, however, be proportional to the increase in area because the average wind speed must be decreased. In the absence of any guidance from experience it will be assumed (iv) that the average wind speed is reduced in the same proportion as the area is increased, i.e. that if the trees on a given area of ground increase the effective area λ times, then the average wind speed is $1/\lambda$ times the average over the treeless area. Using these assumptions a new value of E_a is obtained, E'_a say (Appendix, para. 14), where E'_a is greater than E_a because the increased area more than compensates for decreased wind speed. For an orchard

$$E_T'=\frac{\Delta H_T+\gamma E'_a}{\Delta+\gamma/SD} \qquad (10)$$

PART II. FIELD RESULTS

7. Sugar Beet at Milford, Surrey

During the first year of the experiments (Penman, 1949) direct sampling at the end of July gave a measured soil water loss equal to the calculated value based on $E_T/E_o=0{\cdot}8$. A check of the new analysis, therefore, [illegible] a demonstration that the ratio given by equations 9 and 5 lies between [illegible] and 0·9, limits which must be accepted because of uncertainties in both the sampling technique and the theoretical analysis. Unfortunately, the [illegible] cannot be made because L_s for sugar beet is unknown, but by using a range of reasonable values of L_s a corresponding set of values of E_T/E_o [illegible] calculated to give a check on order of magnitude. The values so [illegible] (Table 1) show the degree of sensitivity of the ratio to changes in [illegible] of L_s.

Table 1. *Theoretical value of* E_T/E_o

Assumed L_s (cm.) . . .	0·08	0·16	0·32
Calculated E_T/E_o . . .	0·75	0·68	0·58

Discussion must be brief. Values of L_s less than 0·08 are probably [illegible] unreasonable, so the reason for the rather low values of E_T/E_o probably [illegible] in neglect of other field factors such as (i) the greater roughness of [illegible] of sugar beet as compared with an area of short grass; (ii) air movement within the crop; (iii) a reflection coefficient less than the value r=0·2[illegible] in this and following examples; and (iv) the evaporation of intercepted [illegible] water. As incorporation of any of these factors in the theory would [illegible] the calculated ratio E_T/E_o, the values in Table 1 may be regarded as [illegible] factory.

8. *Lucerne at Griffith, N.S.W., Australia*

Soil moisture measurements were made at intervals between September 1931 and May 1932 under irrigated lucerne (West, 1933). From these it [illegible] been possible to decide that the soil moisture content was approximately the same on 31 December as on 31 May, i.e. the total evaporation in the period was equal to the sum of rainfall and irrigation. The total was 21 inches. From contemporary weather data, and using Prescott's (1940) equation to calculate incoming solar radiation from duration of bright sunshine (based on Australian records and differing slightly from that for S.E. England), the calculated total, assuming $L_s=0{\cdot}16$ cm., is 22 inches. Over the same period observations of open water evaporation gave a total of 34·5 inches; the calculated value is 33 inches. As an alternative form of check the observed value of E_T/E_o is 0·61, and the calculated value is 0·67. Although these [illegible] ments are encouraging they must be accepted with caution, because (a) there is no *a priori* reason for setting $L_s=0{\cdot}16$, (b) the lucerne showed occasional signs of water shortage, and (c) lucerne is not a good test crop, for [illegible] water is plentiful there is night opening of the stomata (Loftfield, 1921).

9. *Peach Trees at Tatura, Victoria, Australia*

In irrigation experiments at the State Research Orchard the main [illegible] has been the nature of the surface cover between the trees. Of all treatments that most amenable to test is the white clover block, being the only one [illegible] remain green and actively transpiring throughout the summer. It requires more water than any other. Irrigation is by flooding and, in effect, brings the top 2 feet of soil back to field capacity whenever the soil moisture deficit reaches about 2 inches. Apart from possible errors in measuring the water applied, there is a known tendency to over-water to the extent of perhaps one-tenth inch per irrigation (which is drained off), so during the normal [illegible] applications there may be about 1 inch added per season in excess of requirement. Occasionally, this excess may be augmented when heavy rain [illegible] irrigation causes some run-off.

The simplest geometrical figure for a peach tree is an inverted cone, at least until the weight of fruit begins to pull the branches down. The Tatura trees are 15 feet high and in rows 18 feet apart. Treating them as hedges of

[illegible] section 15 feet across at the top, the ratio of tree to ground area is about 2·5, i.e. including the area of cover crop, the area ventilated is 3·5 times as much as if the trees were absent.

Weather records are taken on the Station near the experiment and the only important unknown is, as before, the quantity L_s. As an expedient, to avoid guessing a value has been calculated from the data for the period November 1951 to January 1952: it is $L_s=0{\cdot}16$ cm., and has been used for the remainder of the 1951–52 season and for the three preceding seasons. The complete data for 1951–52 appear in Fig. 1, which shows the seasonal trend. It is

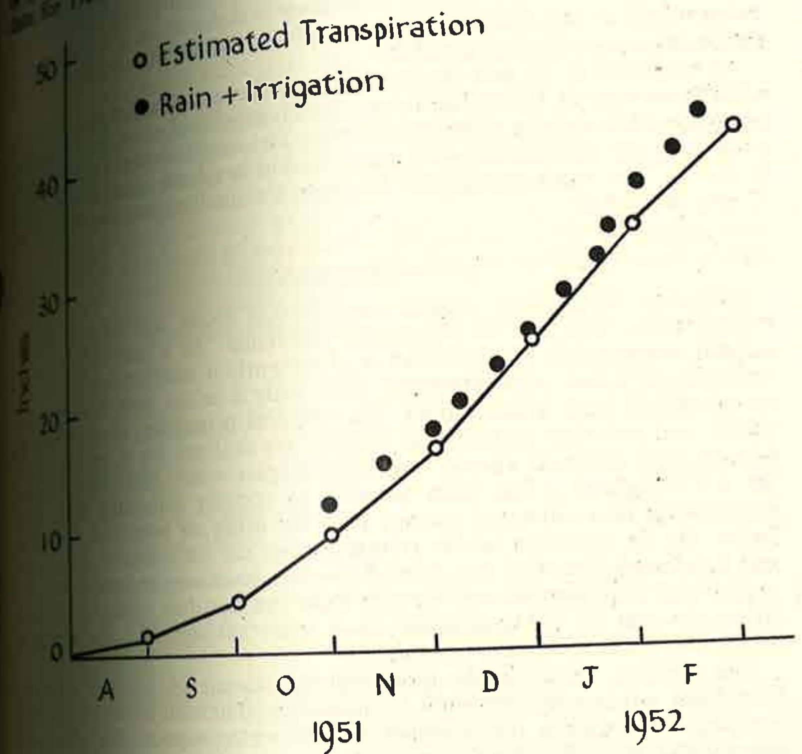

Fig. 1. *Seasonal trend of water use at Tatura, Victoria (peach trees with white clover cover crop)*

possible that an initial soil moisture deficit at the beginning of August and subsequent over-watering to the extent of 1 or 2 inches can together account for the observed values lying consistently above the calculated values. The yearly totals are in Table 2.

Table 2. *Estimated and observed water consumption (inches)* *(Peaches over white clover: Tatura: Aug.-Feb.)*

Season	Irrigation	Rain	Total	Estimated transpiration
1948–49 . .	27·6	9·6	37·2	40·1
1949–50 . .	26·8	13·4	40·2	36·0
1950–51 . .	29·8	11·5	41·3	44·2
1951–52 . .	38·2	5·9	44·1	40·7

As the discrepancies are of the order to be expected from [illegible] uncertainties in the basic physical theory, it seems that the [illegible] and approximations have not greatly increased the uncertainty. This [illegible] illusory, for the value of L_s was chosen to give good agreement [illegible] observation and estimation over a period of three months, and it [illegible] said that the new analysis has merely replaced one empirical [illegible] another. Even after conceding this, progress can be claimed: (i) the [illegible] L_s chosen for a short period fits the four whole seasons; (ii) the [illegible] not very sensitive to changes in L_s (see Table 1); (iii) the value used [illegible] ally and biologically reasonable; (iv) some day independent measurement [illegible] it will be possible; and (v) the new empirical factor is a crop [illegible] independent of the climatic and geographical factors that were part of [illegible] previously used empirical constant.

An extension of the new analysis offers further encouragement. One of [illegible] other treatments at Tatura has a straw mulch as ground cover, and by [illegible] adequate allowance for changed reflection factor and changed area of [illegible] lated crop the average seasonal transpiration has been calculated as [illegible] 33 inches. The totals of rain and irrigation for the four seasons were [illegible] 32 and 26 inches.

SUMMARY

Irrigation designed to replace transpiration losses can be controlled [illegible] transpiration rates can be adequately estimated. As a particular form [illegible] natural evaporation, transpiration is dominantly a weather-controlled [illegible] nomenon in which plant character plays only a minor part, and rates [illegible] be calculated from weather data. The physical principles, involving energy supply and turbulent transport of vapour, are outlined for open water [illegible] because they are most clearly revealed for open water; and second, [illegible] for S.E. England it has been possible to convert estimated open water evaporation into estimated transpiration by using an empirical conversion factor. By an extension of the principles and the introduction of stomatal and day-length factors it has proved possible to eliminate local factors [illegible] to estimate transpiration rate directly from weather data without first [illegible] ating the rate for a hypothetical open water surface. The special case [illegible] orchard crops is separately treated.

Field checks, chiefly in the more extreme climate of southern Australia, have been satisfactory, but only by accepting somewhat arbitrary values [illegible] stomatal conductance for diffusive flow of water vapour. The checks [illegible] equally successful for short crops and for orchard crops.

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APPENDIX

10. *Units and Symbols*

All quantities of energy are expressed in evaporation equivalents: 1 [illegible] evaporation=59 cal./cm.[2]. The main symbols are as follows:

T_a mean air temperature (°F.);
T_s mean surface temperature;
T_d mean dew-point temperature;

[illegible] saturation vapour pressure at mean air temperature (mm. Hg.);
[illegible] s.v.p. at mean surface temperature;
[illegible] s.v.p. at mean dew-point temperature (i.e. the actual vapour pressure in the air);
u_2 mean wind speed at 2 metres (miles/day);
[illegible] evaporation per day (mm.). In order: general, open water surface, transpiring surface;
[illegible] heat transport per day (equivalent mm.);
[illegible] incoming short-wave radiation per day (equivalent mm.);
R_B outgoing long-wave radiation per day;
[illegible] daily heat budget at surface;
r reflection coefficient of surface;
γ conversion factor (mm. Hg./°F.). This is the constant of the wet and dry bulb psychrometer, and =0·27;
Δ slope of s.v.p. curve at T_a (mm. Hg./°F.);
L_a 'effective length' of external atmosphere (cm.);
L_s 'effective length' of leaf surface;
N maximum possible duration of bright sunshine;
n actual duration of bright sunshine;
[illegible] an intermediate expression obtained in calculation (mm./day).
[illegible] In order: for ordinary crops, for orchard with cover crop, and for orchard with straw mulch;
[illegible] ratio of orchard leaf area to ground area.

[illegible] *Formulae*

(i) Transport equations

$E = f(u)\,(e_s - e_d)$;
$K = \gamma f(u)\,(T_s - T_a)$;
$E_o = 0{\cdot}35\,(1 + u_2/100)(e_s - e_d)$;
$E_a = 0{\cdot}35\,(1 + u_2/100)(e_a - e_d)$;

(ii) Heat budget equations

$H = R_c\,(1 - r) - R_B$;
$H_o = 0{\cdot}95\,R_c - R_B$;
$H_T = 0{\cdot}80\,R_c - R_B$;
$R_B = \sigma T_a^4\,(0{\cdot}56 - 0{\cdot}09\sqrt{e_d})\,(0{\cdot}10 + 0{\cdot}90\,n/N)$,

where σ is Stefan's constant.

R_c, if not measured, can be estimated:

$= R_A\,(0{\cdot}18 + 0{\cdot}55\,n/N)$ for S.E. England,
$= R_A\,(0{\cdot}25 + 0{\cdot}54\,n/N)$ for southern Australia,

where R_A is incoming radiation that would reach the site in the absence of [illegible] atmosphere and clouds.

$H = E + K$.

(iii) Combined estimate

$E_o = (\Delta H_o + \gamma E_a)/(\Delta + \gamma)$.

(iv) Penman and Schofield equation

$$\frac{E_T}{E_o} = \frac{e_{sT} - e_d}{e_{so} - e_d} \cdot \frac{L_a}{L_a + L_s} \cdot \left(\frac{N}{24} + \frac{a}{b} \cdot \frac{1}{\pi}\,\mathrm{Sin}\,\frac{N\pi}{24}\right)$$
$$= \frac{e_{sT} - e_d}{e_{so} - e_d} \cdot S.D.$$

[illegible] $E_T = f(u)\,(e_{sT} - e_d)\,SD$.

12. *Determination of S and D*

(i) The stomatal factor, $S = L_a/(L_a + L_s)$.

From equation 1 and using the known coefficient of molecular [illegible] of water vapour in air (0·25 cm.²/sec.) it is possible to show that

$$L_a = 0{\cdot}65/(1 + u_2/100).$$

Table 3 gives values of S for a range of values of u_2.

Table 3. *Dependence of S on u_2 and L_s*

L_s / u_2	0·08	0·16	0·32	0·64
0	0·89	0·80	0·67	0·50
50	0·84	0·73	0·57	0·40
100	0·80	0·66	0·50	0·33
150	0·77	0·62	0·45	0·29
200	0·73	0·58	0·41	0·26
250	0·71	0·54	0·37	0·23
300	0·67	0·50	0·33	0·20

As an indication of order of magnitude, values of L_s at or near 0·16 [illegible] would be obtained for leaves with cylindrical tube stomata and the following characters:

Fractional area (%)	2	1	0·5	2	1
Population (per mm.²)	50	100	400	100	200
Thickness of epidermis (μ)		2·5		5	
L_s (calculated: cm.)	0·17	0·18	0·17	0·14	0·17

(ii) The day-length factor, $D = N/24 + (a \text{ Sin } N\pi/24)/b\pi$.

This is slightly modified from Penman and Schofield (1951), where [illegible] was used to make allowance for the long English twilight.

The ratio a/b is the ratio of two vapour differences, but if leaf and air temperatures do not differ greatly it may be simplified to a temperature difference ratio:

$$\frac{a}{b} = \frac{(T_a \text{ max.} - T_a \text{ min.})/2}{T_a \text{ mean} - T_d}$$

i.e. half the daily range over the excess of daily mean over dewpoint temperature. Values of a/b exceeding unity may occur and may be accepted with caution. They correspond to dew formation, which has to be re-evaporated as open water. The value of D must never be allowed to exceed unity.

For reference the following table is given.

Table 4. *Components of D dependent on season and latitude*

N	$N/24$	(Sin $N\pi/24$)/π	N	$N/24$	(Sin $N\pi/24$)/π
6	0·25	0·225	18	0·75	0·225
7	0·29	0·255	17	0·71	0·255
8	0·33	0·275	16	0·67	0·275
9	0·38	0·295	15	0·62	0·295
10	0·42	0·310	14	0·57	0·310
11	0·46	0·315	13	0·54	0·315
12	0·50	0·320			

[illegible] use the field check on sugar beet (Part II, para. 7) is for June and July (N=16·4). For this site the effective day length has been [illegible] one hour longer, i.e. N has been taken as 17½ hours. From the temperature records a/b=1·48 for June and =1·05 for July. Rigorous substitution in the formula would give D>1·0 for June and the value D=1·0 was [illegible]. For July substitution gives D=0·97, and this value was used.

[illegible] *Determination of E_T*

The two basic equations are:

$$E_T = f(u)\,(e_{sT} - e_d)\,SD;$$
$$H_T = R_c\,(1 - r_T) - R_B;$$
$$= E_T + K_T;$$
$$K_T = \gamma\, f(u)\,(T_s - T_a);$$
$$= \gamma\, f(u)\,(e_s - e_a)/\Delta;$$
$$= \gamma\, f(u)\,(e_s - e_d)/\Delta - \gamma\, f(u)\,(e_a - e_d)/\Delta;$$
$$= \gamma\, E_T/\Delta SD \quad - \gamma\, E_a/\Delta;$$

i.e. $H_T = E_T + \gamma E_T/\Delta SD \quad - \gamma\, E_a/\Delta$

Hence: $$E_T = \frac{\Delta H_T + \gamma E_a}{\Delta + \gamma/SD}$$

[illegible] *Orchard Crops*

[illegible] *area.* Assuming that rows are effective hedges, all that is [illegible] the cross-section normal to the wind. In the case considered this [illegible] as triangular, and the relative increase in ventilated area is the [illegible] of the triangle divided by the separation of the hedges. For trees [illegible] high and 15 ft. across, separated by 18 ft. at the base, the perimeter is [illegible] ft., and the ratio about 2·5. The total ventilated area is thus about [illegible] what it would be if the trees were absent. For other shapes and [illegible] the ratio will be different: suppose it to be λ.

[illegible] *Reduced wind speed.* The assumption is that if u_2 is the wind speed over [illegible] ground, the average wind speed over the ventilated area is u_2/λ.

[illegible] This reduced wind speed affects the stomatal term S (Table 3) and the [illegible] E_a. The latter becomes

$$E_a' = \lambda 0{\cdot}35\,(e_a - e_d)\,(1 + u_2/100\,\lambda);$$
$$= E_a + 0{\cdot}35\,(e_a - e_d)\,(\lambda - 1).$$

[illegible] there is an inert ground cover (e.g. a straw mulch) the value of E_a [illegible]

$$E_a'' = (\lambda - 1).\ 0{\cdot}35\,(e_a - e_d)\,(1 + u_2/100\,\gamma).$$

[illegible] example, if u_2=140 m.p.d., u_2/λ=40 m.p.d. and for L_s=0·16 the value of the stomatal factor, S, is increased from 0·63 to 0·75; and the values of E_a, E_a' and E_a'' are 0·84 $(e_a - e_d)$, 1·72 $(e_a - e_d)$ and 1·22 $(e_a - e_d)$.

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BIOLOGICAL INVESTIGATIONS INTO THE VALIDITY OF *CONTARINIA* SPECIES LIVING ON THE CRUCIFERAE, WITH SPECIAL REFERENCE TO THE SWEDE MIDGE, *CONTARINIA NASTURTII* (KIEFFER)*

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(With Plate 6)

Biological investigations have proved that *Contarinia nasturtii* (Kieffer), *C. isatidis* Rübsaamen and *C. ruderalis* (Kieffer) are in reality one species. The names *C. isatidis* Rübsaamen and *C. ruderalis* (Kieffer) are therefore synonyms of *C. nasturtii* (Kieffer). Considerable doubt has been thrown on the authenticity of several other species.

The host plant range of *C. nasturtii* was already known to be very extensive. Fourteen additional host plants, including two tetraploid varieties and several weeds have been added during this investigation. Eight were established by experiments, and the remaining six have previously been recorded as host plants of *C. ruderalis*. In addition, *Brassica nigra*, *Lepidium sativum* and *Rapistrum rugosum* have since been established as host plants of *Contarinia nasturtii* in Holland. *Diplotaxis tenuifolia* and *Lunaria annua* are suspected as host plants, but the evidence is not yet conclusive.

INTRODUCTION AND METHODS

In the past gall midges of the same genus have often been described as distinct species if they occurred on different host plants. This was a useful precaution against confusing species in the absence of more detailed knowledge of the insects concerned. Certain gall-midge species are now known to have a range of host plants, and some show such a gradation in morphological characters when large numbers of specimens are examined that specific determination by the usual methods is difficult. This has led to the development of biological techniques in which studies of life histories, host-plant range and mating tests play a part.

A large number of midges must be available for such work. They can be bred from larvae in galls collected either in the field or from a plot where host plants are extensively grown. This may quickly become infested if the midges are in the vicinity and saves many hours of field searching. The plants can be examined frequently and the midges, bred out from collected galls in emergence cages, are available for biological tests.

Such a plot was established at Rothamsted Lodge, Harpenden, in an investigation of the genus *Contarinia* infesting the Cruciferae. Thirty-four different crucifers (marked with an asterisk in Table 1) were grown, of which ten were known host

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