

ance of a crop like celery on moist soil conditions. Where there is good drainage and a low ground water level, high rainfall does little harm; indeed it leads to better crops. In conditions of poor drainage and high ground water levels excessive rainfall in the growing period can have very serious and harmful results. But where drainage conditions are good, there does appear to be an optimum ground water level for celery in black Fen soils, between 20 and 24 inches below the surface.

It would be misleading, in presenting these results, to leave the impression that high ground water levels are desirable in all circumstances. Indeed other crops in this experiment have responded differently, but it is becoming ever more clear that the soil moisture factor is of vital importance and the result in a particular case is decided by the influence of the weather sequence before and during the life history of the crop involved, conjointly with that of the ground water level in maintaining steady and optimum moisture conditions around the root system.

SUMMARY

Much valuable agricultural land has been obtained by lowering the ground water level in swampy areas. Is there an optimum ground water level for the purposes of agriculture? The history of the Fenland in Britain is outlined and a current experiment on the control of ground water level is described. Three years experience with the celery crop has shown that benefit can be obtained from static ground water levels as high as 20 inches but that in moist summers both yield and quality are depressed by levels higher than 20-24 inches. The celery crop is planted here in early June when normally a moisture deficit is appearing in the soil. The magnitude and time of incidence of this deficit are conditioned by the rainfall sequence of June-September inclusive and can be modified by the control of the ground water. Thus, in a dry summer, a high ground water level gives optimum moisture conditions and a low level gives full play to the limiting influence of an increasing deficit of moisture in the soil. In moist summers this is mitigated to the advantage of the crop above a low water level, but in the presence of a high ground water, water-logging may result from the same rainfall, to the disadvantage of the crop.

RÉSUMÉ

Un grand nombre de terrains utilisables pour l'agriculture ont été obtenus en abaissant le plan d'eau de contrées marécageuses.

Y a-t-il un niveau optimum de l'eau du sol pour les besoins agricoles?

L'histoire de la Fenland en Grande Bretagne est mise en évidence et il est décrit une expérience courante à propos du contrôle du niveau de l'eau.

Trois ans d'expériences avec la culture du céleri ont montré qu'il peut être avantageux de maintenir le niveau de l'eau souterraine à 50 cm., mais que lors des étés humides l'importance et la qualité de la récolte diminuent si le niveau de l'eau à partir du sol est moindre que 50 à 60 cm.

Le céleri est planté ici au début de Juin lorsque le sol n'est plus assez humide. L'importance et la durée de ce déficit sont conditionnées par la série de chutes de pluies de Juin à Septembre inclusivement et peuvent être modifiées par le contrôle du niveau de l'eau souterraine.

Ainsi en été sec, un niveau d'eau élevé procure des conditions d'humidité optimum, et un niveau d'eau bas autorise pleinement l'influence de la sécheresse du sol.

L'été humide est à l'avantage de la récolte si le niveau de l'eau du sol est bas, mais si ce dernier s'élève, il peut y avoir excès d'eau en raison des pluies, au désavantage de la récolte.

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

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 here 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 transport equation for evaporation from open water is

$$E_o = 0.35 (e_s - e_a) (1 + u_a/100) \text{ mm./day,} \quad (1)$$

where e_s and e_a are the vapour pressures at the surface and in the air, in mm. Hg., and u_a 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

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

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

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

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

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

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

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

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 $(e_a - e_a)$, which is the 'saturation deficit' of the air. The evaporation rate from open water then becomes (Penman, 1948 or 1949)

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

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:

- 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).
- 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).
- 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.
- 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 differs from that of an open water surface exposed to the same weather, the vapour pressure difference in the transport equation will not be the same for both surfaces.

The second is more complex. In moving away from an open water surface the vapour encounters resistance at all levels, resistance that is greater the calmer the air. For a given wind speed the total resistance between the surface and the level at which the vapour pressure is measured is presumed constant (a consequence of the first assumption made in this paper), and if the transport were by molecular diffusion only this same resistance would be encountered over a very much shorter distance. Though it is not a very 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 molecular diffusion as the distance between surface and screen height does to turbulent 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 will be the same for all surfaces having the same aerodynamic roughness. By a happy accident the open water and short grass surfaces used in our original experiments appear to have behaved as though equally rough, and hence the 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 in the air, and to it must be added a resistance in the leaf. Arising at the surface of the mesophyll tissue lining a sub-stomatal cavity, the vapour has to diffuse to the inside opening of the stoma, through the epidermis, and then away from the outside opening before merging with corresponding streams from neighbouring stomata: thereafter the vapour flow encounters the external resistance already assessed. If the geometry of the stomata is known and is sufficiently simple the stomatal resistance to flow can be computed as an equivalent length L_s , but information is so scanty, and such geometry as is known is so complex, that this method of estimating stomatal resistance to diffusion is unlikely to be of any general use. An alternative, offering more promise, is the direct technique used by Heath (1941) and Milthorpe (in preparation) to measure the stomatal conductivity for diffusive flow, the reciprocal of which is the 'effective length' of the stomatal array. Assuming it known in some way, then the total effective length for a leafy surface is $L_a + L_s$: for an open water surface it is L_a : and the stomatal factor in E_τ/E_o is $L_a/(L_a + L_s) = S$, say.

The third factor allows for the normal night closure of the stomata and 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 minimum and midday maximum; (iii) the stomata are fully open throughout daylight and completely closed in darkness. The day-length factor then reduces to the sum of two terms, the first being $N/24$ where N is the duration of daylight and so has an annual cycle with an amplitude varying with latitude, and the second being a sine term that becomes less and less important the drier the atmosphere. The sum of the two terms is always less than unity. Representing the factor by D , the Penman and Schofield equation can be written

$$\frac{E_\tau}{E_o} = \frac{e_{s\tau} - e_d}{e_{s_o} - e_d} \cdot S D \quad \dots \quad (6)$$

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

$$E_\tau = f(u)(e_{s\tau} - e_d) S D, \quad \dots \quad (7)$$

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

5. Calculation of Transpiration Rate

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

$$H_\tau = E_\tau + K_\tau \quad \dots \quad (8)$$

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

$$E_\tau = \frac{\Delta H_\tau + \gamma E_a}{\Delta + \gamma/SD} \quad \dots \quad (9)$$

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_τ is less than H_o , then E_τ 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.

6. 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. As 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 new 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

$$E_\tau = \frac{\Delta H_\tau + \gamma E'_a}{\Delta + \gamma/SD} \quad \dots \quad (10)$$

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 $E_T/E_0=0.8$. A check of the new analysis, therefore, only needs a demonstration that the ratio given by equations 9 and 5 lies between 0.7 and 0.9, limits which must be accepted because of uncertainties in both the sampling technique and the theoretical analysis. Unfortunately, this check cannot be made because L_s for sugar beet is unknown, but by using a series of reasonable values of L_s a corresponding set of values of E_T/E_0 can be calculated to give a check on order of magnitude. The values so obtained (Table 1) show the degree of sensitivity of the ratio to changes in value of L_s .

Table 1. Theoretical value of E_T/E_0

Assumed L_s (cm.)	0.08	0.16	0.32
Calculated E_T/E_0	0.75	0.68	0.58

Discussion must be brief. Values of L_s less than 0.08 are probably biologically unreasonable, so the reason for the rather low values of E_T/E_0 probably lies in neglect of other field factors such as (i) the greater roughness of an area 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 $r=0.20$ used in this and following examples; and (iv) the evaporation of intercepted rain-water. As incorporation of any of these factors in the theory would increase the calculated ratio E_T/E_0 , the values in Table 1 may be regarded as satisfactory.

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 has 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 this 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 $L_s=0.16$ 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_0 is 0.61, and the calculated value is 0.67. Although these agreements are encouraging they must be accepted with caution, because (a) there is no *a priori* reason for setting $L_s=0.16$, (b) the lucerne showed occasional signs of water shortage, and (c) lucerne is not a good test crop, for when 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 variable 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 to 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 12 applications there may be about 1 inch added per season in excess of requirement. Occasionally, this excess may be augmented when heavy rain after 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

triangular 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 a guess, a value has been calculated from the data for the period November 1951 to January 1952: it is $L_s=0.16$ 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

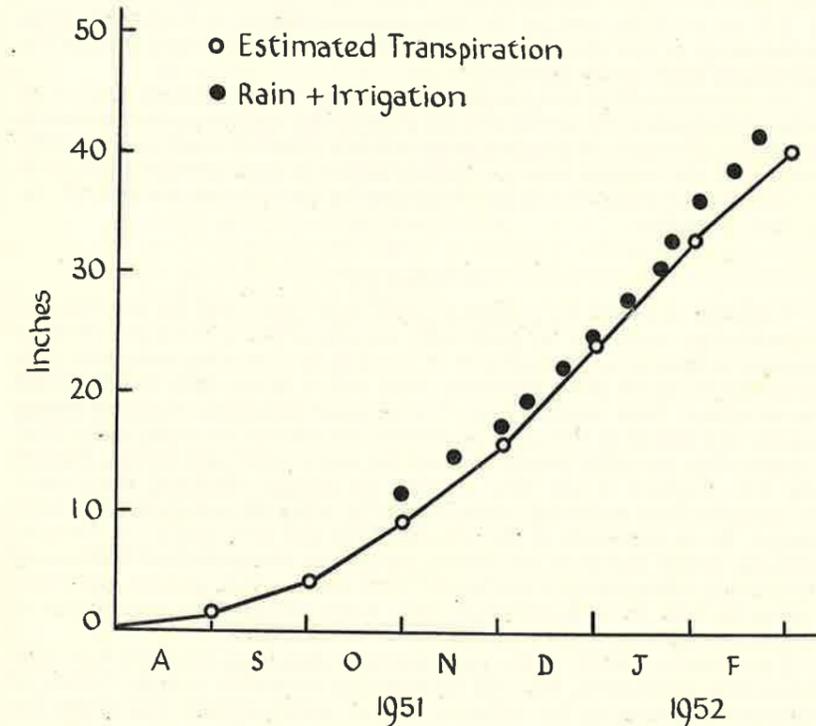


Fig. 1. Seasonal trend of water use at Tatura, Victoria (peach trees with white clover cover crop)

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

An extension of the new analysis offers further encouragement. One of the other treatments at Tatura has a straw mulch as ground cover, and by making adequate allowance for changed reflection factor and changed area of ventilated crop the average seasonal transpiration has been calculated as about 33 inches. The totals of rain and irrigation for the four seasons were 29, 34, 32 and 26 inches.

SUMMARY

Irrigation designed to replace transpiration losses can be controlled if transpiration rates can be adequately estimated. As a particular form of natural evaporation, transpiration is dominantly a weather-controlled phenomenon in which plant character plays only a minor part, and rates can be calculated from weather data. The physical principles, involving energy supply and turbulent transport of vapour, are outlined for open water: first, because they are most clearly revealed for open water; and second, because 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 and to estimate transpiration rate directly from weather data without first calculating the rate for a hypothetical open water surface. The special case of 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 of stomatal conductance for diffusive flow of water vapour. The checks are 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 mm. 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;

e_a	saturation vapour pressure at mean air temperature (mm. Hg.);
e_s	s.v.p. at mean surface temperature;
e_d	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);
E, E_o, E_τ	evaporation per day (mm.). In order: general, open water surface, transpiring surface;
K, K_o, K_τ	heat transport per day (equivalent mm.);
R_c	incoming short-wave radiation per day (equivalent mm.);
R_B	outgoing long-wave radiation per day;
H, H_o, H_τ	daily heat budget at surface;
r, r_o, r_τ	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;
E_a, E'_a, E''_a	an intermediate expression obtained in calculation (mm./day). In order: for ordinary crops, for orchard with cover crop, and for orchard with straw mulch;
λ	ratio of orchard leaf area to ground area.

11. Basic Formulae

(i) Transport equations

$$\begin{aligned} E &= f(u) (e_s - e_d); \\ K &= \gamma f(u) (T_s - T_a); \\ E_a &= 0.35 (1 + u_2/100)(e_s - e_d); \\ E'_a &= 0.35 (1 + u_2/100)(e_a - e_d); \end{aligned}$$

(ii) Heat budget equations

$$\begin{aligned} H &= R_c (1 - r) - R_B; \\ H_o &= 0.95 R_c - R_B; \\ H_\tau &= 0.80 R_c - R_B; \\ R_B &= \sigma T_a^4 (0.56 - 0.09 \sqrt{e_d}) (0.10 + 0.90 n/N), \end{aligned}$$

where σ is Stefan's constant.

R_c if not measured, can be estimated:

$$\begin{aligned} &= R_A (0.18 + 0.55 n/N) \text{ for S.E. England,} \\ &= R_A (0.25 + 0.54 n/N) \text{ for southern Australia,} \end{aligned}$$

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

$$H = E + K.$$

(iii) Combined estimate

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

(iv) Penman and Schofield equation

$$\begin{aligned} \frac{E_\tau}{E_o} &= \frac{e_{s\tau} - e_d}{e_{s_o} - e_d} \cdot \frac{L_a}{L_a + L_s} \cdot \left(\frac{N}{24} + \frac{a}{b} \cdot \frac{1}{\pi} \sin \frac{N\pi}{24} \right) \\ &= \frac{e_{s\tau} - e_d}{e_{s_o} - e_d} \cdot S.D. \end{aligned}$$

$$\therefore E_\tau = f(u) (e_{s\tau} - e_d) S.D.$$

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 diffusion of water vapour in air ($0.25 \text{ cm}^2/\text{sec.}$) it is possible to show that

$$L_a=0.65/(1+u_2/100).$$

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	0.08	0.16	0.32	0.64
u_2				
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 cm. would be obtained for leaves with cylindrical tube stomata and the following characters:

Fractional area (%)	2	1	0.5	2	1	2
Population (per mm. ²)	50	100	400	100	200	100
Thickness of epidermis (μ)	2.5			5		10
L_s (calculated: cm.)	0.17	0.18	0.17	0.14	0.17	0.16

(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 $N+1$ 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	$N/24$	$(\text{Sin } N\pi/24)/\pi$	N	$N/24$	$(\text{Sin } N\pi/24)/\pi$
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			

As examples of use the field check on sugar beet (Part II, para. 7) is for June ($N=16.6$) and July ($N=16.4$). For this site the effective day length has been made one hour longer, i.e. N has been taken as $17\frac{1}{2}$ 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 used; for July substitution gives $D=0.97$, and this value was used.

13. Determination of E_τ

The two basic equations are:

$$E_\tau=f(u) (e_{s\tau}-e_d) SD;$$

$$H_\tau=R_c (1-r_\tau)-R_B;$$

$$=E_\tau+K_\tau;$$

$$K_\tau=\gamma f(u) (T_s-T_a);$$

$$=\gamma f(u) (e_s-e_a)/\Delta;$$

$$=\gamma f(u) (e_s-e_a)/\Delta-\gamma f(u) (e_a-e_d)/\Delta;$$

$$=\gamma E_\tau/\Delta SD - \gamma E_a/\Delta;$$

$$\text{i.e. } H_\tau=E_\tau+\gamma E_\tau/\Delta SD - \gamma E_a/\Delta$$

$$\text{Hence: } E_\tau = \frac{\Delta H_\tau + \gamma E_a}{\Delta + \gamma/SD}$$

14. Orchard Crops

(i) *Ventilated area.* Assuming that rows are effective hedges, all that is needed is the cross-section normal to the wind. In the case considered this was taken as triangular, and the relative increase in ventilated area is the perimeter of the triangle divided by the separation of the hedges. For trees 15 ft. high and 15 ft. across, separated by 18 ft. at the base, the perimeter is about 48 ft., and the ratio about 2.5. The total ventilated area is thus about 3.5 times what it would be if the trees were absent. For other shapes and sizes the ratio will be different: suppose it to be λ .

(ii) *Reduced wind speed.* The assumption is that if u_2 is the wind speed over open ground, the average wind speed over the ventilated area is u_2/λ .

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

$$E_a' = \lambda 0.35 (e_a - e_d) (1 + u_2/100 \lambda);$$

$$= E_a + 0.35 (e_a - e_d) (\lambda - 1).$$

If there is an inert ground cover (e.g. a straw mulch) the value of E_a becomes

$$E_a'' = (\lambda - 1) \cdot 0.35 (e_a - e_d) (1 + u_2/100 \gamma).$$

As an example, if $u_2=140 \text{ m.p.d.}$, $u_2/\lambda=40 \text{ m.p.d.}$ 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 $1.22 (e_a - e_d)$.

RÉSUMÉ

L'irrigation calculée pour remplacer les pertes par transpiration peut être conduite correctement si les taux de transpiration peuvent être estimés de façon satisfaisante.

La transpiration est un cas particulier du phénomène naturel de l'évaporation. Elle est contrôlée de façon dominante par les conditions climatiques dans lesquelles les caractères propres de la plante jouent seulement une part réduite, de sorte que les taux de transpiration peuvent être calculés d'après les données climatologiques. On expose ici les principes physiques, com-

prenant la fourniture d'énergie et le transport de vapeur par turbulence, qui interviennent dans le cas de l'eau libre, d'abord, parce que ces principes apparaissent plus clairement dans un tel cas et ensuite parce que pour le Sud-Est de l'Angleterre, il a été possible de convertir l'évaporation calculée pour l'eau libre en transpiration par l'emploi d'un facteur empirique de conversion. Par une extension de ces principes et introduction de facteurs relatifs aux stomates et à la longueur du jour, on a prouvé qu'il était possible d'éliminer les facteurs locaux et d'estimer les taux de transpiration directement d'après les données climatiques sans calculer d'abord le taux relatif à une surface d'eau libre hypothétique. Le cas spécial d'un verger est traité séparément.

Les épreuves aux champs, principalement dans le climat le plus extrême du Sud de l'Australie ont été satisfaisantes mais seulement en admettant des valeurs quelque peu arbitraires pour la conduction par les stomates du courant diffusant de vapeur d'eau. Les épreuves ont été également satisfaisantes pour des cultures de courte durée et pour des vergers.

REFERENCES

- BLANEY, H. F., and CRIDDLE, W. D. (1950). 'Determining Water Requirements in Irrigated Areas.' Soil Conservation Series, U.S.D.A., Washington.
 HEATH, O. V. S. (1941). *Ann. Bot.*, N.S. 5: 455.
 LOFTFIELD (1921). 'The Behaviour of Stomata.' Carnegie Inst., Washington.
 PASQUILL, F. (1950). *Q.J. Roy. Met. Soc.* 76: 287.
 PENMAN, H. L. (1948). *Proc. Roy. Soc. A.* 190: 120.
 PENMAN, H. L. (1949). *Q.J. Roy. Met. Soc.* 75: 293.
 PENMAN, H. L. (1951). *B.J. App. Phys.* 2: 145.
 PENMAN, H. L. (1952). *J. Agric. Sci.* 42: 286.
 PENMAN, H. L., and SCHOFIELD, R. K. (1951). S.E.B. Symposium, No. 5, 115.
 PRESCOTT, J. A. (1940). *Trans. Roy. Soc. S. Australia* 64: 114.
 SWINBANK, W. C. (1951). *J. Meteorology* 8: 135.
 THORNTHWAITE, C. W. (1951). *Weatherwise* 4.
 THORNTHWAITE, C. W., and HOLZMANN, B. (1939). *Monthly Weather Rev.*, Washington 67: 4.
 WEST, E. C. (1933). *Australian C.S.I.R. Bull.* 74.

Irrigation Investigations in Dutch Fruit Growing

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INTRODUCTION

THE National Organizing Committee for the Thirteenth International Horticultural Congress has asked me to deliver a paper about Irrigation Investigations in Dutch Fruit Growing. Though research in the field of artificial water-supply in the Netherlands only started some years ago, I thought it best to comply with this request, because it offers an opportunity for a discussion of original conditions, the methods followed with one's research and the possible results obtained.

Of results of experiments and investigations I can only tell you very little and I shall principally have to confine myself to giving the causes which have induced us to carry out research in the field of artificial water-supply in the Netherlands, to discussing the design of some experiments and researches and to state some experiences gained in the Netherlands.

Causes of research

The Netherlands have a moist climate. The average annual rainfall amounted to 720 mm. (about 30 in.) a year during the years 1901-40. This was distributed in the months as follows (in mm.):

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
57	42	46	50	48	59	71	74	65	74	65	64

The average monthly temperature in degrees Centigrade is:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2.3	2.6	4.9	7.9	12.4	15.0	16.7	16.2	13.7	9.6	5.2	2.7

On studying these figures superficially, one does not get the impression that it is necessary for the Dutch people to worry about water-supply of crops, especially when one considers that the rivers Scheldt, Meuse and Rhine and some smaller ones annually convey besides the rainfall great quantities of water to the Netherlands.

The Netherlands are of old famous for being a country where the people have struggled against a surplus of water for ages, where dykes have kept out the high tides (about 40 per cent of the Netherlands are below sea level) and where large pumping plants have had to drain off the superfluous water from the interior.

Till some years ago one thought only in terms of drainage in the Netherlands. Until about 1925 there were many districts which were too wet for useful agricultural exploitation. Examples were to be found in the river clay region and the sea clay region of Sealand, where only the higher levels had been drained and not the lower ones. After 1925 work was started with the higher sandy soils in the Eastern and Southern part of our country, the lower parts of which were also too wet. Here also the agricultural engineers carried out works to drain these lowest levels sufficiently.

Little research was carried on into the depth of drainage which was most wanted. In the calculation of width and depth of ditches and the capacity of pumping installations it was assumed that plants in grassland were shallow rooting, and in arable land, deep rooting. Therefore grassland was drained less deeply than arable land. Furthermore, the deepest drainage was supposed to be the best.