Rothamsted Experimental Station Report for 1972 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1972

PART 2

Full Table of Content

Water Use by Farm Crops II. Spring Wheat, Barley, Potatoes (1969); Potatoes, Beans, Kale (1968)

B. K. French, I. F. Long and H. L. Penman

B. K. French, I. F. Long and H. L. Penman (1973) *Water Use by Farm Crops II. Spring Wheat, Barley, Potatoes (1969); Potatoes, Beans, Kale (1968)* ; Rothamsted Experimental Station Report For 1972 Part 2, pp 43 - 61 **- DOI: https://doi.org/10.23637/ERADOC-1-34687**

Water Use by Farm Crops

II. Spring Wheat, Barley, Potatoes (1969); Potatoes, Beans, Kale (1968)

B. K. FRENCH, I. F. LONG and H. L. PENMAN

Summary

Testing continued, revealing two new sources of distorted readings. For wheat (clearly) and barley (less clearly) in 1969, the first severe drying was over-estimated by the meter, and this is attributed to soil shrinkage in the top layer, 0 to 30 cm. A correction factor, α, was found by assuming that the true drying in a period, D_c, is given by $D_c = \alpha D_1 + D_2$ where D_1 and D_2 are as measured, 0 to 30, and 30 to 150 cm, respectively; that $E = D_c + R = \kappa E_T$ for the period; and that κ is constant for any two consecutive periods. Solving pairs of simultaneous equations gave scattered values of α, but selecting unity or the greater value less than unity out of two gave an adequate correction curve. (For wheat the maximum correction made for this error was 17 mm, and at O sites the final whole-season correction was 11 mm. For barley the maximum was 10 mm, and the final value 8 mm.) The second source of distortion is peculiar to the crop—ridged potatoes, where half of the top 30 cm of 'soil' is empty air. By trial, internal coherence of results was achieved by using $D_c = 2D_1/3 + D_2$, where D_1 and D_2 are for the ranges 0 to 20, and 20 to 150 cm. This weighting factor is used in all potato results, here and in Part III. In 1968 the experiments were on a small scale, the summer was wet, and all meter problems were flooding and drainage problems.

Wheat, 1969. At O sites, three (out of four) sets of replicate measurements agreed extremely well throughout the summer, and all four agreed well in the whole season balance. At I sites ($\Sigma I = 110$ mm in four applications) one was suspect from the start; the other three agreed well. For the whole season, to harvest, $\Sigma E_O = \Sigma E_I$ before and after correction: within the season, for individual periods, $E_O \simeq E_I$ after correction. There seemed to be no check to transpiration at O sites, where the maximum soil moisture deficit, D_O, reached 165 mm (plus 17 before correction).

Barley, 1969. Agreements in duplicate measurements were often poor and the scale of the corrections is not much greater than that of experimental scatter. Up to the time of the third of three irrigations ($\Sigma I = 68$ mm) $\Sigma E_O \simeq \Sigma E_I$ (more exactly after correction), but thereafter $E_I > E_O$, the divergence starting at $D_O \simeq 130$ mm (plus 10 before correction). Just before harvest $E_I - E_O \simeq 15$ mm.

Potatoes, 1969. Duplicate measurements agreed fairly well, but all are suspect, partly because of the need for a weighting factor, and partly because the plants and the ridge faces steered irrigation and rain water to the furrow bottom, beyond the range of action of the meter. At I sites ($\Sigma I = 129$ mm in five applications) it seemed that nearly all the water was taken out of the ridge, with little coming from below 30 cm depth. At O sites only about 60 cm of soil profile were tapped. Below about 90 cm, at all sites, there was barely a detectable change in soil water content throughout the season. There was a check to transpiration at O sites when $D_O \simeq 25$ mm, and $E_I - E_O$ then increased to *c*. 60 mm just before harvest.

https://doi.org/10.23637/ERADOC-1-7

Potatoes, 1968. There was great scatter in the pairs of duplicate measurements ($\Sigma I = 39$ mm in two June applications) particularly in July and August when there was much rain. There was slight evidence of a short-lived check at O sites when $D_O \simeq 15$ mm, but over the whole season E_O and E_I were not detectably different.

Beans, 1968. There was more irrigation than on the potatoes, with more flooding and drainage problems in processing. Very approximately, E_I began to exceed E_O at $D_O \simeq 50$ mm, and before harvest, $E_I - E_O \simeq 30$ or 40 mm.

Kale, 1968. A patch of kale, not irrigated, had four access tubes and was monitored three times, at monthly intervals. Results showed the same erratic variation in replicates as were found for sugar beet, but they were not in conflict with more extensive measurements in 1967 and 1971 (Part III).

For all six crops, $\kappa > 1$.

Introduction

Part I describes an exhaustive test of the accuracy of the meter assembly, and the results, for 1970, were satisfactory, provided that quality control of readings was thorough and that anomalous readings could be rejected. Rigid definition of 'anomalous' is impossible, but after close examination of hundreds of soil moisture profiles some sort of judgement is possible, and is needed in two sets of circumstances. The first is independent of the accuracy of the meter, and is an uncertainty rather than an anomaly. The meter can measure only changes in water content, and when there is a decrease it cannot partition the change into upward movement (evaporation) and downward movement (drainage): because of the properties of the local soil, downward movement of water can occur when the profile is drier than at field capacity. In general, small amounts of suspected drainage are ignored and are included in the evaporation estimates but where there is confidence that a large amount of drainage occurred the records for the relevant period are set aside as misleading and some other way is found to fill the gap.

The second, more serious, group of problems arises from the major defect of the meter as a scientific instrument. Its response is almost wholly determined by the water content of the soil within a few centimetres of the outside of the access tube, and if, for any reason, there is a horizontal gradient of water content then the meter reading does not give the average water content at the level of measurement. The extreme form of this, usually easily recognised, is accumulation of water in the space between the outside of the access tube and the soil around it, more often detected at irrigated sites, but only rarely does it affect more than the bottom 30 cm of the profile. Occasionally, near the surface, the opposite effect is detected, strongly suspected to be the effect of plant roots getting into (or very close to) the gap, but even without this special bias there is a source of distorted readings dependent on the nearness of the root system to the access tube. Because the access tubes are always set in the plant rows, in a period of net drying the amount of drying may be over-estimated, and in a period of net wetting the gain may be over-estimated too. Under a uniform crop cover, with not too severe changes, this biased error may be perhaps 5% of the change, or about half of the random error in the estimate of the change. The bias tends to be self correcting as the season progresses, and it was ignored in analysis of the 1970 results. An extreme form, not negligible, occurred in 1969, suspected of being caused by shrinkage of the soil away from the outside of the access tube, and will be considered in context later (spring wheat, 1969). A root crop is not a uniform crop however geometrically exact the plant spacing, and the meter response is determined by the behaviour of the nearest plant, or pair of plants. These are facets of differential extraction of water, but there are also possibilities of differential wetting,

https://doi.org/10.23637/ERADOC-1-7

depending on how plant structure steers rain or irrigation water to the soil. Potato plants are very efficient umbrellas and during irrigation there may be water standing in the furrows while the tops of the ridges show little sign of re-wetting.

Part II continues the testing aspect of meter performance, sometimes without full reasons for decisions. Two years are covered, with 1969 giving some periods of severe drying, including one week in June with more than 100 hours of sunshine, so that the soil/meter/plant system got an imposed stress unique in the ten years of available records. There were full supporting measurements in micrometeorology and growth analysis of the spring wheat on the macroplots. In due course, the 1969 results will probably be used as a major source of tests of ideas on soil, plant and weather interactions. In contrast, 1968 produced little of value. The macroplots were not in use (left fallow for cleaning operations to eliminate weeds), the late summer was wet, and of the two crops irrigated the potatoes probably got too much water, and the beans certainly got too much, because of rain that fell soon after the irrigations. There was occasional trouble with both instruments—now several years old—leading to re-design of the circuit, and the building of two new meters for use in 1969 and later.

Spring wheat, 1969

The crop (Kolibri) was drilled on 6 April 1969 at 18 cm spacing on sites Mn and Ms (Fig. 1, I). It emerged about 15 April and on 12, 13 and 14 May four access tubes were inserted on each site. From early May there had been 24 mm of rain up to 12 May, and there was 1 mm more to 14 May. The difficulties of installation were as usual, but almost from the first reading onward it was thought that at least one I site (SW tube) readings were unreliable from 70 cm depth downward. Examination of the records confirmed this, and raised doubts about the others (Fig. 2, and discussion of it).

The plants grew slightly better on the O plots than on the I plots, with a margin of about 3% in plant density and a corresponding difference in leaf area index that reached 3 by the end of May, attained its maximum near 6·5 about 20 June and then declined to 2 by the end of July and almost to zero before harvest on 4 September. At the same epochs the crop height and fractional cover were: end of May, 40 cm, 60%; 20 June, 80 cm, 95%; end of July, 125 cm, 90%.

There were four applications of irrigation, each near 25 mm, and intended to keep the soil moisture deficit near 25 mm. As in 1970, the average amount received at an I site was the mean of the catch in five small collectors round the site, with a standard deviation near 10%. The nominal total, measured by water meter in the pipe-line was 102 mm: the individual measured average values were: NE 125, SE 100, SW 124 and NW 91 mm. Neutron meter readings were taken at about weekly intervals and, wherever possible, on the day before an irrigation operation. One was taken after harvest.

Seasonal water balance. The results for the wheat, and to a lesser extent for the barley (see later) contain very unwelcome scatter of a kind not found in the results for 1970: the meter is still on trial. Before looking at detail, the whole season balance will be considered briefly to show what the detail has to explain.

Fig. 1, top left, gives the accumulated values of $D_O - D_I$, period by period, and the accumulated average irrigation for the season. All four replicates are included, and the whole depth of monitoring (0 to 150 cm) is used. There was no irrigation in the first two periods. At the end of the first, $\overline{D_O - D_I}$ was 29 mm, and for one of the future I sites $\bar{D}_O - D_I$ was >50 mm: the total rain was only 34 mm, i.e. this, the SW site, appeared to gain more water than fell as rain. Ignoring the first readings, and starting from a fresh zero at the end of Period 1, Fig. 1 results, with several features of interest

https://doi.org/10.23637/ERADOC-1-7

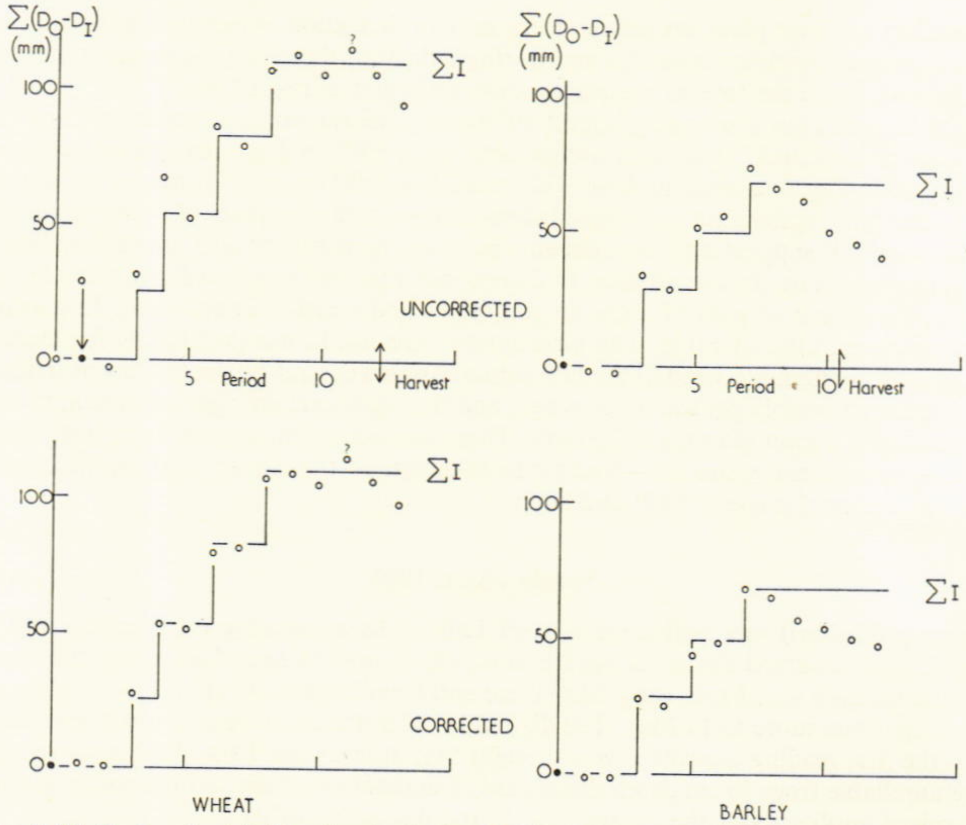

FIG. 1 (II). Spring wheat (left) and spring barley (right), 1969. Periodic changes in $\Sigma(\bar{D}_O - \bar{D}_I)$ compared with contemporary values of ΣI, before and after correction. Full point is working zero.

and challenge. First, ignoring the measurements after harvest, the distribution of the last four points suggests that the evaporation rates were not detectably different at O sites and I sites in the weeks before harvest, so there is a strong presumption that this equality existed before Period 8. Secondly, at the end of Period 8, after the last irrigation, $\Sigma(D_O - D_I) = \Sigma I$, suggesting as the least complicated explanation, that all the irrigation water had stayed in the profile and that total evaporation from the O sites and the I sites had been the same: again the strong inference is that this must have been true in the individual periods. Yet clearly (and thirdly) this seems to be contradicted by the detail. For the first three irrigations the apparent relative gain at I sites (vertical interval between points) is greater than the measured irrigation (vertical rises in full line). Where there is a measurement to guide, i.e. after the second and third irrigations, there is evidence of a recovery with an overshoot. Study of the records suggested that the meter was over-estimating changes in $D_O - D_I$ by amounts that altered during the summer, and correction factors were sought that would take out most of the anomalies, after some quality control had eliminated a few observations that could be disregarded for good reasons. The result is in the lower part of Fig. 1, and the link between the two parts now follows.

Drying in selected periods (Fig. 2). All the analysis is based on layers 30 cm thick. The first period, 22 May to 2 June, had no irrigation, so the eight sets of readings should be replicates, and they are not. Each of the four sub-diagrams shows the integrated accumulation of water in the profiles after 34 mm of rain and 11 days of evaporation (the pairing

https://doi.org/10.23637/ERADOC-1-7

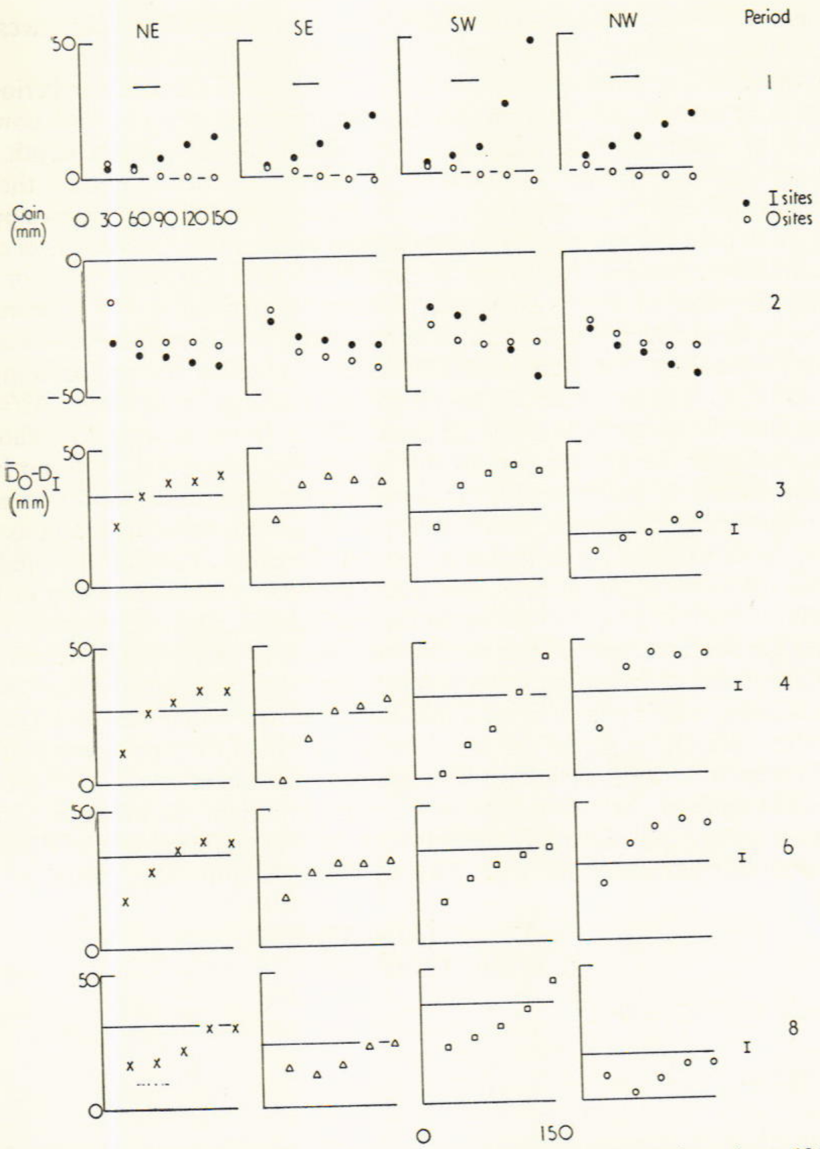

FIG. 2 (II). Accumulated changes in water content, 0 to 150 cm, under spring wheat, 1969. Periods 1 and 2: no irrigation: the horizontal line in Period 1 is at the rainfall in it. Periods 3 to 8: the horizontal line represents the irrigation.

is irrelevant). All of the O sites show an accumulation of water to 30 cm depth, and then a decrease probably representing drainage of surplus water that was in the profile (or round the access tubes) on 22 May, and had drained away before the rain started. All of the I sites show accumulation to 30 cm—about the same as at O sites—and then more: the SW site apparently collected 48 mm of water, with no hint of a limit.

In later water balances only the results for 0 to 30 cm will be used for Period 1.

Period 2, again with no irrigation, showed remarkable consistency at three O sites, with a greater drying at the SE site that was to be accentuated in Period 3. This very close agreement among NE, SW and NW O sites persisted throughout the season, and their mean values of D_O will be used in nearly all that follows, as representative of what happened on the unirrigated plots. (In the end, the omitted site produced the same ΣD

https://doi.org/10.23637/ERADOC-1-7

as the others—Table 2.) At the I sites there were no unacceptable differences down to 90 cm, either within themselves or in comparison with O site readings.

In later water balances only the results for 0 to 90 cm will be used for Period 2.

The next four sets of sub-diagrams are for the irrigation periods, and now it is the relative gain of water, expressed as $\bar{D}_O - D_I$, that is plotted against depth, with the measured amount of irrigation ($\pm$ about 10%) shown. Except in Period 8 the anomaly is persistent at all sites: the apparent gain is greater than the irrigation applied and usually by more than the uncertainty in the amount of irrigation. Some sort of correction is needed, and some possible routes can be considered from the NE results for Period 3. The asymptotic value of $\bar{D}_O - D_I$ is near 40 mm, the irrigation was 33 mm, and the value of $\bar{D}_O - D_I$ at 30 cm was 22 mm. The first possibility—in arithmetic—is to subtract 7 mm from all readings, but there is no semblance of physical reason for doing so. The second possibility, slightly better, is to weight all readings by a factor 33/40 on the assumption that the meter is in error by about 20%. To do so over the whole profile to 150 cm, and over the greater part (if not all) of the season will have no important effect on the pattern of points on Fig. 1: it will simply bring them all down, and automatically produce the conclusion that the evaporation from the irrigated plots exceeded that from those unirrigated up to Period 8, but not thereafter. The third possibility, to be used, is that the meter is not at fault, but that the severe and rapid drying in Periods 2 and 3 produced shrinkage and cracking in the surface soil, most severe near the access tubes where the surface roots of the plants were, perhaps providing preferred channels that would steer rain or irrigation water towards the tubes, and, around the O site tubes, perhaps producing an air gap of several millimetres between tube and soil. (Laboratory tests, in water, with an air gap of 3·3 mm over only 5 cm of tube produces a decrease in reading of about 6%. Until shrinkage was complete the meter would over-estimate net drying.) So the basis of correction is to be the need to weight the net drying in the first 30 cm only, and the scale of what is needed—but not the preferred way of doing it—can be found from this particular NE case. The weighting factor, α say, would be obtained from

$$\underset{(0\text{ to }30)}{\alpha 22} + \underset{(30\text{ to }150)}{(40 - 22)} = 33$$

which gives $\alpha = 15/22 = 0{\cdot}7$.

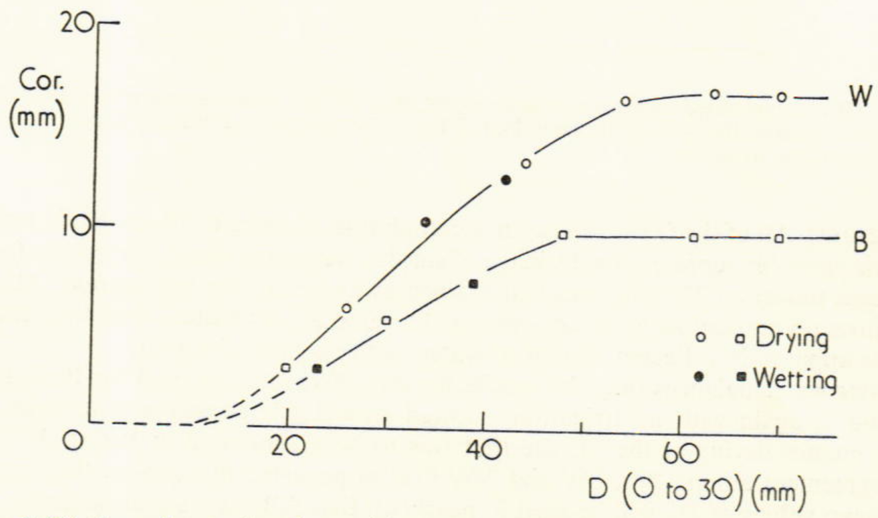

FIG. 3 (II). Corrections to be subtracted from D (0 to 30 cm) for wheat (W) and barley (B).

https://doi.org/10.23637/ERADOC-1-7

This technique applied to all other cases gives widely fluctuating values of α, and in any event, is for irrigation periods only. The effect of irrigation is to decrease the value of D_I relative to D_O, i.e. the magnitude of corrections to D_I will be smaller than those for D_O, so it seems reasonable to seek a correction for D_O and assume it will apply to D_I too, and thus avoid the effect of uncertainties in the amount of irrigation applied.

Experience suggests that during the main part of the growing season the actual rate of evaporation (E) is proportional to the potential rate (E_T). The basis for correction is the assumption that this is true for any pair of consecutive periods, for each of which the value of E will now be given by

$$E = \alpha D_1 + D_2 + R = \kappa E_T \qquad 1, \text{II}$$

where D_1 is for 0 to 30, and D_2 is for 30 to 150 cm. With E_T known, pairs of simultaneous equations can be set up and solved for α (and κ). When this was done for the average values of D_1 (three sites) the results, though scattered, were acceptably coherent. Except for the first and last (Periods 2 and 8) two values of α emerged for each period (for Periods 7 and 8, $\alpha = 1{\cdot}00$ anyway), and thence two values of αD_1. Choosing the bigger of the two (i.e. minimising correction), values of $\Sigma(1-\alpha)\,D_1$ were plotted against ΣD_1, starting from $(1-\alpha)/2$ for Period 2, to give the correction for subtraction from ΣD_1. This is on Fig. 3, with the corresponding curve for the barley, needed later. For Periods 1 and 9 to 13, α was taken as unity.

Seasonal changes by layers

O sites. Fig. 4, left, gives the uncorrected changes in water content from a zero at the end of Period 1. Down to 120 cm it probably shows the gradual deepening of root action, but from 120 to 150 cm the decline may represent slow drainage, and, if so, will be an under-estimate of total drainage from the profile. One point is queried (Period 11, 0 to 30 cm). It seems to be some 10 mm or so below the trend from 10 to 13. Here it is in the mean of 3, but the phenomenon occurred at all O sites, and it did not occur at I sites, nor under the barley, monitored on the same day but with a different meter. Below

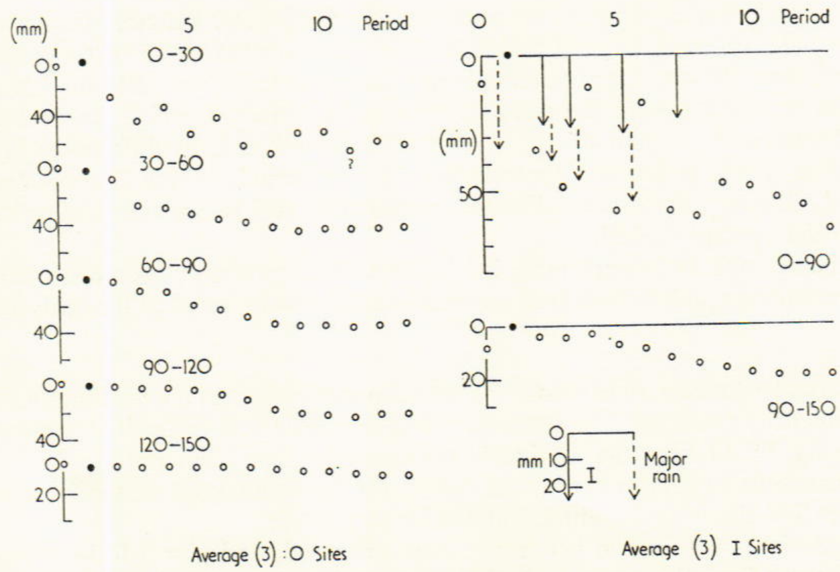

FIG. 4 (II). Left. Average drying, by layers, at O sites under wheat, 1969. Right. On more open scale, drying 0 to 90 (with I and major rain), and 90 to 150 cm at I sites. Full points show working zero.

https://doi.org/10.23637/ERADOC-1-7

30 cm depth all four O profiles are normal: it is equally difficult to invent a reason why a meter should go wrong four times over the first part of its traverse, as it is to invent a soil or plant behaviour that affected four sites to about the same extent.

I sites. Fig. 4, right, is simpler. The average is for three sites, omitting SW for reasons given. The upper part, 0 to 90 cm, includes irrigation amounts and rain in early periods, and the evidence is that some of the rain in Period 1 could have been lost as drainage, but all subsequent rain and irrigation were probably retained. In the later water balance no allowance is made for any possible drainage below 90 cm. The lower part, 90 to 150 cm, shows the characteristic distortion caused by what is thought to be flooding round the bottom of the access tube. It may have cleared itself by the end of Period 6, and the subsequent drying of 10 mm may represent drainage from the profile. To permit results for site SW to be taken in, the water balance for I sites will be restricted to the range 0 to 90 cm, to the end of Period 8, and 0 to 150 cm thereafter.

TABLE 1(II)

Wheat, 1969. Average periodic drying (corrected), and probable evaporation (mm)

	Period	R	$\bar{D}_O$ (3)	$\bar{D}_I$ (4)	I	$\overline{I+D}$	$R+\overline{I+D}$	ΣE_T
1	21/5–2/6	33·6	−3·4	−4·1	—	−3·8	30	31
2	2/6–9/6	3·6	26·1	25·6	—	25·8	29	55
3	9/6–19/6	12·7	39·3	12·4	25·5	38·6	51	85
4	19/6–25/6	18·8	−1·0	−26·9	28·0	0·0	19	99
5	25/6–2/7	0·2	30·7	32·6	—	31·8	32	121
6	2/7–10/7	25·0	2·2	−26·0	29·7	2·9	28	144
7	10/7–17/7	0·3	30·0	27·8	—	28·9	29	166
8	17/7–24/7	0·0	27·4	2·3	26·8	28·2	28	187
9	24/7–31/7	25·4	−6·6	−8·6	—	−7·6	18	201
10	31/7–7/8	16·2	0·7	4·9	—	2·8	19	217
11	7/8–21/8	17·4	17·5?	7·8	—	(7·8)	25	250
12	21/8–29/8	9·6	−6·6?	2·4	—	(2·4)	12	269
13	29/8–30/9	10·1	0·5	8·5	—	4·5	15	309

Possible evaporation (Fig. 5). With the need for corrections, and so many uncertainties that appear as highly improbable coincidences, the final water balance, as an estimate of actual evaporation must be very tentative. It is based on the mean of three sites for O treatments, 0 to 150 cm except where already noted, and on four sites for I treatments, 0 to 90 cm or 150 cm, with the same exceptions in Periods 1 and 2. Table 1 gives the corrected values of D_O and of $D_I + I$ for each period and, as differences are trivial, their average is used to derive E up to Period 10. For Periods 11 and 12, only D_I is used: for Period 13, after harvest, the difference is probably real (more weeds after irrigation) but again the average is used.

The general slope, before ripening, is 1·3, but this has probably been distorted upward by the corrections applied. Note that the small scatter was imposed as the basis for corrections.

Full season water balance, to harvest. Table 2 shows the effect of corrections and rejection of untrustworthy readings. The correction was applied to all individual measurements, including the SE O site, and obviously no distortion has been produced by ignoring SE measurements to get a more precise datum for $\bar{D}_O$ in analysis. In the I site balances, the suspect SW site is outstanding, but not by very much.

The agreements within and between groups are good, and give a little extra support to the inference from the upper part of Fig. 1 that there is no detectable difference in the total water use at O and I sites.

https://doi.org/10.23637/ERADOC-1-7

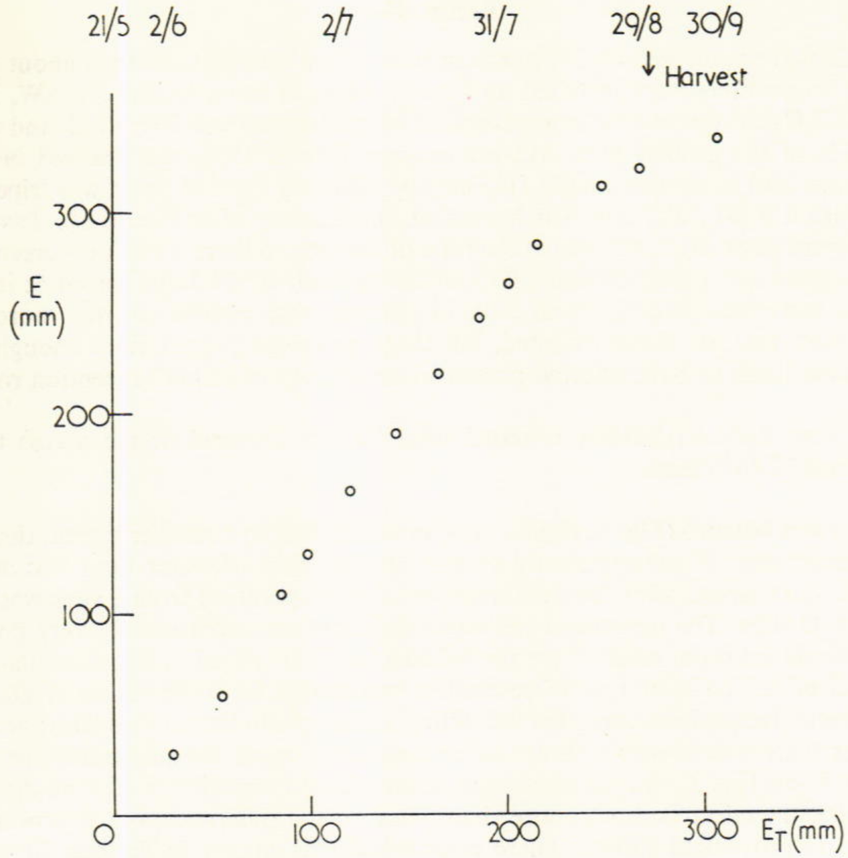

FIG. 5 (II). Evaporation from spring wheat, 1969. Average for O and I sites.

TABLE 2(II)

Wheat, 1969. Water balance to harvest (mm)

Periods		R	NE D_1	NE D_2	SE D_1	SE D_2	SW D_1	SW D_2	NW D_1	NW D_2
	(O)									
1, 2	(a) 21/5–9/6	37	32	19	43	25	37	25	39	28
3 to 8	(b) 9/6–24/7	57	144	133	157	147	137	126	135	123
9 to 12	(b) 24/7–29/8	69	9	9	−2	−2	0	0	9	9
	Σ	163		161		170		151		160
	$\Sigma R + D_2$			324		333		314		323
	(I)									
1, 2	(a)	37	24	24	12	23	−2	17	25	25
3 to 8	(c)	57	16	12	41	24	15	16	49	35
9 to 12	(b)	69	−11	−8	10	10	23	21	3	4
	Σ	163		28		57		54		64
	I			124		100		125		91
	$\Sigma R + I + D$			315		320		342		318

Nominal $I = 102$ mm
$\Sigma E_T = 269$ mm
D_1 = drying, 0 to 150 cm: from uncorrected meter readings
D_2 = drying, corrected. (a) 0 to 30, 0 to 90; (b) 0 to 150; (c) 0 to 90

https://doi.org/10.23637/ERADOC-1-7

Barley, 1969

Variety Zephyr was drilled on 29 March in rows 18 cm apart. It emerged about 10 April and four access tubes were installed on 7 and 8 May, in rows, on site Xs, SW, NW (O) and NE, SE (I). At the first meter readings, 23 May, the crop was 30 cm tall, and covering about 55% of the ground area. Maximum cover (about 95%) was reached before the end of June, and maximum height (115 cm) by mid-July (Period 7). It was 'ripe' by the end of Period 9 (31 July) and was harvested immediately after Period 10. Two sets of readings were taken after harvest: at the time of the second there was a new green growth of weeds, grass and barley covering 80% of the ground. By 24 July (Period 8: irrigation complete) there was lodging on all plots in patches, with possibly a little more on unwatered plots than on those irrigated, but there was none judged close enough to any of the access tubes to have affected presumed uniformity of rainfall reception round the tubes.

There were three irrigations, nominal total 70 mm, metered at the access tubes as 64 (NE) and 72 (SE) mm.

Seasonal water balance (Fig. 1, right). As for wheat, but to a smaller extent, there is the same phenomenon of an apparently greater relative gain of water than was added as irrigation. In contrast, after the final irrigation the evaporation from I sites was greater than from O sites. The agreement between duplicates was occasionally very poor, and some of the deviation of points from the full line for ΣI is caused by experimental scatter, but not all of it. The same type of correction was sought from the values of D_O, R and E_T in consecutive periods, using the individual values of D_O for the two sites: because of the scatter there was always a choice to be made, and again the minimum was chosen. The result is on Fig. 3, and the maximum accumulated correction is 10 mm. Applied to D_O and D_I, the effect is rarely more than 5 mm in the difference, but it produced the significant improvement shown. There is an additional change in Periods 10 to 12, to be explained later.

Seasonal changes by layers. The averages of duplicate readings are on Fig. 6. Agreements for individual periods were often poor, but improved in consecutive periods, and only Period 10 needs special comment. At O sites the agreement was good, the values

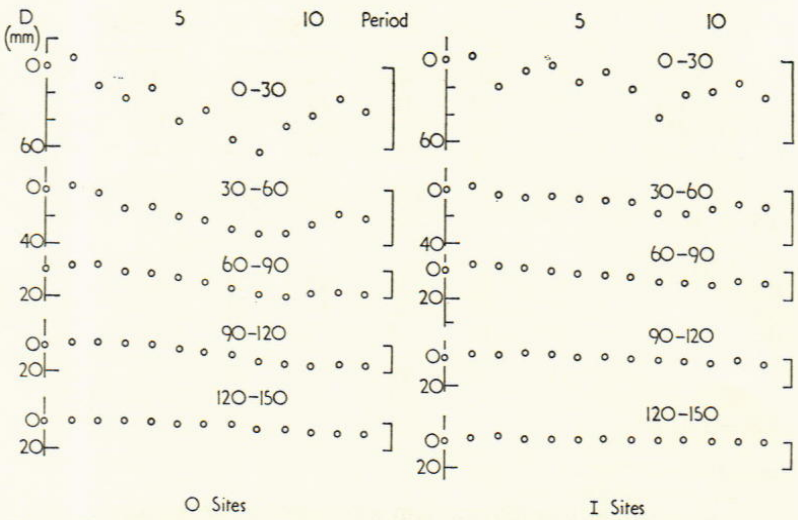

FIG. 6 (II). Average drying, by layers, barley 1969. Left, O sites; right, I sites.

https://doi.org/10.23637/ERADOC-1-7

of δW, 0 to 90 cm, being: SW, 18·7; NW, 18·4 mm, and 0 to 150 cm they were: SW, 14·3; NW, 16·7 mm. At I sites the agreement was poor, with corresponding values for 0 to 90 cm, of: NE, −0·4; SE 11·1 mm, and, for 0 to 150 cm, NE, −4·2; SE, 12·4 mm. There was meter trouble on the day of the 10/11 monitoring, but not of a kind to justify blaming the meter for the discrepancy of 16·6 mm in the duplicate estimates of water balance at I sites in Period 10. Because the gain at the SE I site is concordant with gains at both O sites, this alone is used in Figs. 1 and 7, and the record for Period 10 at the NE I site is ignored.

TABLE 3(II)

Barley, 1969. Average periodic drying, 0 to 150 cm, (corrected) and probable evaporation (mm)

	Period	R	$\bar{I}$	$\bar{D}_O$	$\bar{I}+\bar{D}_I$	E_O	E_I	ΣE_T
1	23/5–5/6	37·0	—	−16·4	−14·6	21	22	35
2	5/6–10/6	0·0	—	25·8	26·2	26	26	52
3	10/6–20/6	16·0	28·3	23·6	22·0	40	38	81
4	20/6–26/6	15·5	—	−3·4	0·0	12	16	96
5	26/6–4/7	0·2	21·2	33·9	35·8	34	36	121
6	4/7–11/7	25·4	—	0·4	−4·1	26	21	141
7	11/7–17/7	0·0	18·7	33·6	32·8	34	33	163
8	17/7–25/7	0·0	—	26·2	28·0	26	28	184
9	25/7–31/7	25·4	—	−16·2	−7·7	9	18	197
10	31/7–13/8	20·8	—	−14·0	−11·2?	7	10?	228
11	13/8–28/8	22·6	—	−17·2	−13·0	5	10	261
12	28/8–18/9	7·6	—	11·4	14·4	19	22	281

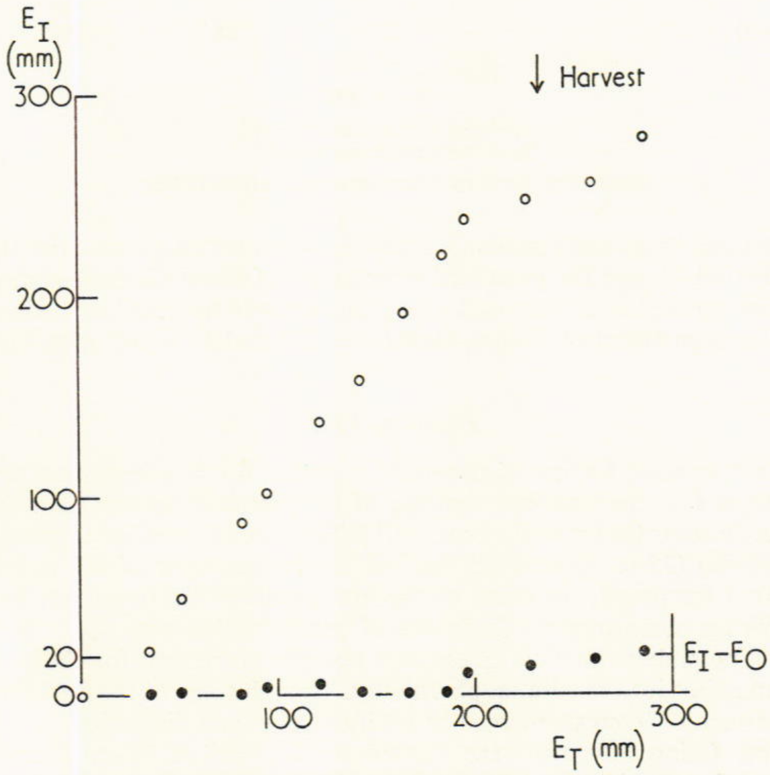

FIG. 7 (II). Evaporation, E_I, from irrigated barley, 1969, and difference, $E_I - E_O$.

https://doi.org/10.23637/ERADOC-1-7

Probable evaporation. With this one omission, Table 3 and Fig. 7 show the seasonal change in water balance and evaporation, after correction of values of $\bar{D}_O$ and $\bar{D}_I$. For clarity, only E_I is plotted in total, and the accumulated difference, $E_I - E_O$, is given separately. The effect of the correction is to produce a slight increase in the slope of the line of points—value near 1·25—and, as for the wheat, the method of correction has decreased the scatter. The first important excess of E_I over E_O occurred after Period 8 (15 July) when the average measured deficit at O sites was 140 mm, corrected to 130 mm. At harvest, $E_I - E_O \simeq 15$ mm.

Whole season water balance, to harvest. To show the effects of corrections and averaging, Table 4 gives the water balance at each site, in three groups of periods, the middle group

Table 4(II)

Barley, 1969. Water balance to harvest (mm)

			O				I			
			SW		NW		NE		SE	
Periods	(cm)	R	D_1	D_2	D_1	D_2	D_1	D_2		D_2
1, 2	0–90	37	17		15		18		23	
	0–150		12	9	12	10	15	12	14	11
3 to 7	0–90	57	82		84		22		5	
	0–150		96	88	94	86	27	27	9	10
8 to 10	0–90	46	−23		−15		18?		9	
	0–150		−11	−10	−1	2	24?	23?	11	11
Σ		140		87		98		<62?		32
I								64		72
$\Sigma R + I + D$				227		238		<266?		244

Nominal $\bar{I} = 70$ mm
$\Sigma E_T = 228$ mm

D_1 = net drying, uncorrected
D_2 = net drying, corrected

Correction for 0 to 90 cm same as for 0 to 150 cm

including the three irrigation periods (3, 5 and 7). The queried values arise from the uncertainty in Period 10, and the presumed error here—of about 12 mm—is more than the total correction applied at O sites, and very much exceeds the total correction applied at I sites. With an adjustment of 12 mm, then $\bar{E}_O = 233$ and $\bar{E}_I = 249$ mm, for a total E_T of 228 mm.

Potatoes, 1969

The crop is not suitable for use of the neutron meter, for two important reasons. The first, not new, is that the inter-row spacing of the plants is greater than the range of sensing of the detector (as for sugar beet, 1970). The second, peculiar to potatoes, is that because of ridging (25 to 30 cm high) half of the surface layer of soil to this depth is empty air. As it happened, the effect of the first produced no important discrepancies between duplicate measurements (a source of great trouble with sugar beet in 1970) so that it was possible to make a guess at a possible correction for the second effect, try it and then adjust it to maximum plausibility. Though some of the final numbers may be suspect, enough of interest emerged to justify display and discussion.

The potatoes (King Edward) were planted on 17 April at 38 cm spacing in rows 70 cm apart, and were ridged on 21 April, leaving a slightly flattened ridge top 25 cm

https://doi.org/10.23637/ERADOC-1-7

above the furrow bottom. The access tubes were inserted in the ridges (3 and 4 June) with the tops at the flattened ridge tops. The plants emerged 12 to 16 May, and by the time of the first monitoring (5 June) were about 20 cm tall and covering 20 to 25% of the ground. The block was area Xn, with duplicate tubes at O sites, NW and NE, and at the I sites, SW and SE, designed to receive maximum irrigation. Five applications, nominally equal, were very nearly so, and the average total, monitored as 129 mm, almost coincided with nominal total 127 mm. By 4 July (Period 5) plants at O sites were wilting, while those at I sites were not and were bright green. At the beginning of August (Period 9) the plants had passed their maximum height (80 cm, I sites; 70 cm, O sites) and were sprawling at heights 65 cm, I, and 55 cm, O. This may have affected distribution of later rain and irrigation: the agreement between duplicates was a little worse in the remaining five periods (though still good). The leaves were yellowing at the end of August (Period 12). Harvest was a week after the last monitoring on 12 September.

Search for a correction factor. A diagram such as Figs. 1 and 6 was useless because there was strong evidence of drainage, and very early in the season the unirrigated plots had a severe check to transpiration, wilting in Period 5. A guess was made that over the range 0 to 20 cm depth the correct value of *D* would be only one-half that measured, and from 20 to 150 cm no correction would be needed. Making reasonable estimates of possible drainage—evidence to come—a seasonal water balance was worked out, and in the form of a precursor of Fig. 9 it showed coherent sections with two major discontinuities. The nature and position of these suggested that evaporation was being under-estimated and drainage was being over-estimated, and an increase in the weighting factor would help to eliminate both sources of error. The new choice, two-thirds instead of one-half, was the final choice and is used in all that follows. The trial graph showed a general slope of about 1·20 to 1·25, and the bigger value was used, for three periods only, to give some precision to estimates of drainage.

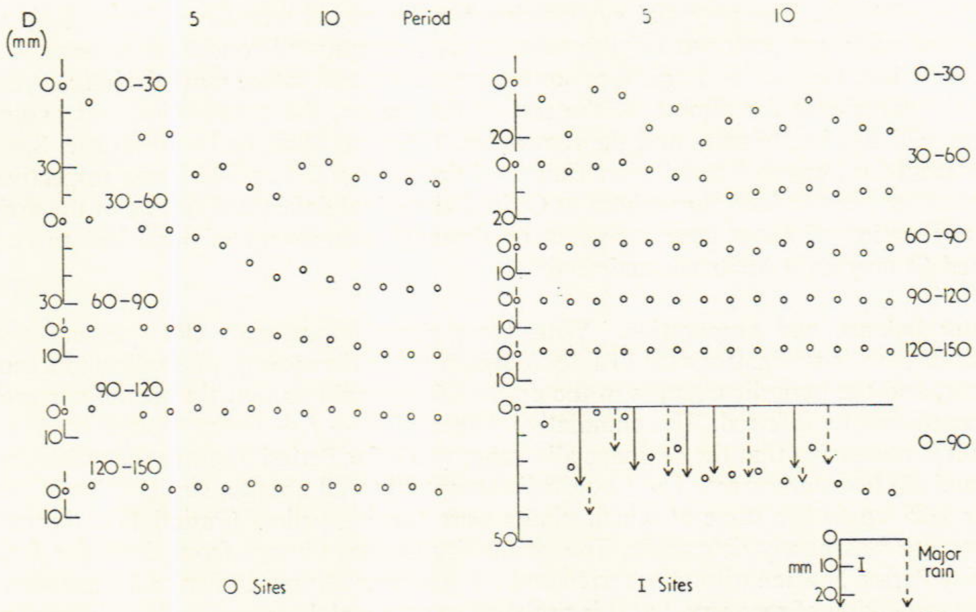

FIG. 8 (II). Average drying, by layers, potatoes 1969. Left, O sites; right, I sites with 0 to 90 cm on more open scale.

https://doi.org/10.23637/ERADOC-1-7

Seasonal changes by layers. Starting from zero at the first monitoring (perhaps 10 mm or so drier than field capacity in the disturbed surface layers), the average drying, corrected for 0 to 30 cm, is on Fig. 8. There is something new here, not affected by surface uncertainty. In the two deepest layers for O sites, and in the three deepest for I sites, there is remarkable constancy of water content, indicating that there was no net movement of water through these parts of the soil profiles. It is easier to accept that the equal inputs and discharges were, in fact, zero, i.e. that these profiles had reached an equilibrium by early June that was in no way affected later by plant action above, by rain, or by irrigation. Yet there was drainage from the irrigated plots, and the failure to detect it is a consequence of the two factors identified at the start of this section. In general, an upright potato plant sheds its rain and irrigation water outward, and when irrigated, there can be standing water in the furrows while the soil at ridge top still looks dry. This flood water is beyond the range of action of the neutron moisture meter and cannot be detected by it. The drainage characteristics of the soil are such that downward movement of surplus water must occur with very little spread horizontally, and it is a fair inference that even at 150 cm depth the percolating water was still too far from the access tube for its presence to be noticeable.

Remembering that the meter response is not discontinuous at a discontinuity in soil water content, it seems that the irrigated plants took nearly all of their water from the ridge while those not irrigated drew on possibly no more than 60 cm depth of soil profile. Ridging as a technical device seems to be a poor way of managing the water relations of potatoes.

The last diagram of Fig. 8 gives the integrated drying to 90 cm depth from zero at the first monitoring. Full lines give average irrigation and broken lines rainfall when it might be important in the context of possible drainage. Periods 3, 5 and 7 are the only ones that present real problems, with the first and third outstanding. The accumulated deficit, from the chosen zero, on 17 June was about 23 mm under the I plots. Immediately after the measurement, on the same day, 29·5 mm of irrigation were applied, and then in the next two days there were 11·2 mm of rain. Monitored again on 20 June the deficit had decreased by 21·5 mm: the three-day water balance thus gave loss $= 29{\cdot}9 + 11{\cdot}2 - 21{\cdot}5 = 19{\cdot}6$ mm. The potential evaporation for the period was $E_T = 7$ mm. Rejecting the possibility that three wet English summer days reproduced conditions to be expected in the Sudan, the 'loss' is ascribed to some evaporation and rather more drainage. Applying the experience for almost all the rest of the season, the evaporation was assumed to be $1{\cdot}25\ E_T$, i.e. 8·7 mm, and the remainder, 10·9 mm, attributed to drainage. Similar treatment for Periods 5 and 7 gave estimated drainage of 2·4 and 11·1 mm respectively: in all other periods (and throughout at O sites) the initial deficit and timing of the arrival or application of water were such that no drainage component of 'loss' had to be invoked (it may have occurred, undetected).

Water balance and evaporation. With these three adjustments the seasonal water balance sheet is straightforward (Table 5). It is given as the average of duplicate measurements, and the periodic changes in the drying, D, are split so that the size of correction imposed can be inferred. The cumulative values of $R + I + D$ are plotted on Fig. 9, and it is reassuring that the drainage allowance made for Period 3 brings the estimates of E_I and E_O into agreement. The I points lie acceptably well about a straight line of slope near 1·25 up to the stage at which plants were turning yellow (Period 12): thereafter water use was barely detectable. The points for O sites diverge from those for I sites during Period 5, when wilting occurred and D_O was near 25 mm. In Period 6 there seemed to be some kind of recovery, but it is probably experimental error. The final difference in estimated water use was 60 mm, and the whole season water balance of Table 6 shows a

https://doi.org/10.23637/ERADOC-1-7

TABLE 5(II)

Potatoes, 1969. Water balance and probable evaporation (*mm*)

	Period	R	O D_1	O D_2	O $R+\Sigma D$	I	I D_1	I D_2	I $R+I+\Sigma D$	ΣE_T
1	5/6–10/6	0·0	4·8	−2·6	2·2	—	4·5	0·6	5·1	17
2	10/6–17/6	4·8	No reading		—	—	8·5	9·4	22·7	40
3	17/6–20/6	11·2	8·3	10·9	35·2	29·9	−13·4	−8·1	8·7*	47
4	20/6–26/6	15·5	−0·8	1·2	15·9	—	2·8	−1·8	16·5	61
5	26/6–4/7	0·3	8·3	7·1	15·7	23·3	7·9	8·4	37·5*	91
6	4/7–11/7	25·4	−3·7	6·1	27·8	—	−6·0	2·5	21·9	106
7	11/7–18/7	0·0	4·4	7·4	11·8	26·8	9·2	2·6	27·5*	128
8	18/7–25/7	0·0	2·6	11·4	14·0	25·3	−8·6	7·3	23·8	150
9	25/7–1/8	25·4	−9·1	−3·9	12·4	—	−0·7	−1·6	23·1	162
10	1/8–8/8	16·2	1·0	0·4	17·6	—	5·5	−1·7	20·0	180
11	8/8–14/8	4·6	4·2	8·2	17·0	23·7	−8·4	−4·7	15·1	195
12	14/8–28/8	22·6	−1·5	5·3	26·4	—	5·4	10·4	38·4	226
13	28/8–3/9	0·3	2·0	1·8	4·1	—	2·8	−0·8	2·3	236
14	3/9–12/9	0·2	1·1	2·9	4·2	—	1·4	0·9	2·5	246

* Assumed = 1·25 E_T for period

$D_1 = \frac{8}{9}$ Measured D (0–20)

$D_2 =$ Measured D (20–150)

little of the detail of how it was reached, with the duplicates separated to show the quality of agreement. Expectation is that major difference between SW and SE I sites should come in only after the last period of through drainage, and the test is that the late irrigation at site SE should exceed that at site SW by about 20 mm. The excess is only 8 mm, possibly significantly smaller than expectation.

In the total balance, on averages, the estimated wasted irrigation is 25 mm, equal to the sum of the calculated drainage amounts in Periods 3, 5 and 7.

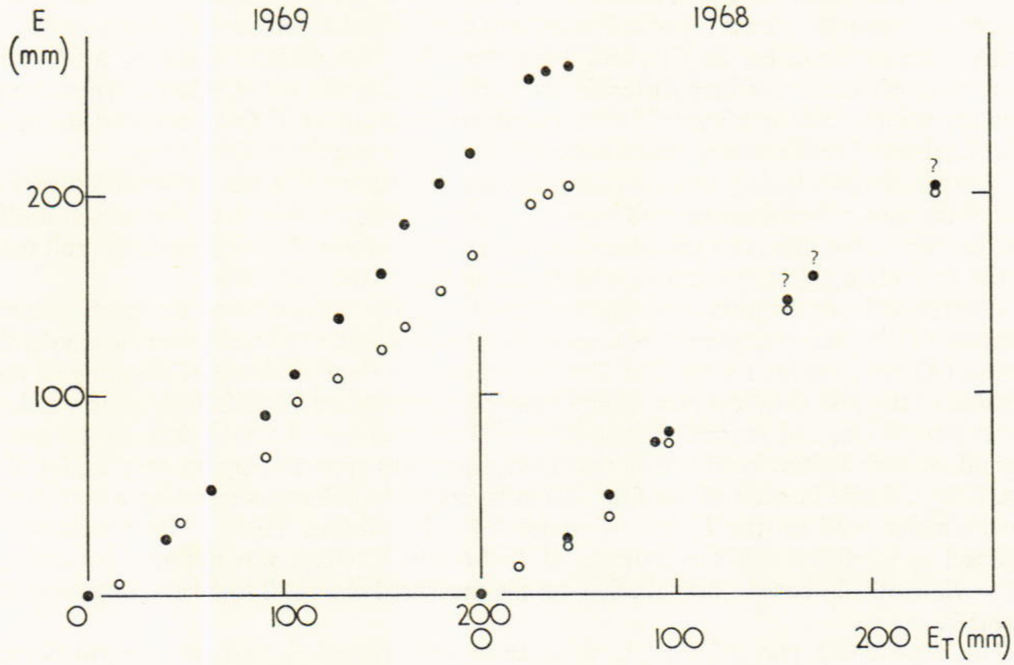

FIG. 9 (II). Evaporation from potatoes, 1969 and 1968. Full points, I sites; open points, O sites.

https://doi.org/10.23637/ERADOC-1-7

TABLE 6(II)

Potatoes, 1969. Whole season water balance (mm)

Periods 0–14. Corrected net drying (D)

(cm)	O NW	O NE	I SW	I SE	
0–30	38	36	25	14	
0–60	60	65	44	19	
0–90	68	79	45	22	
0–120	71	83	46	22	
0–150	72	84	47	22	
I Periods	3, 5, 7		75	84	
I Periods	8, 11		45	53	
Average D	78		34		
Average I	—		129		Nominal = 127
R	126		126		
$R + I + D$	204		289		
Processed E	204		264		$E_T = 246$
			Wasted I 25		

Potatoes, 1968

Majestic potatoes were planted on 3 April at 38 cm spacing in rows 71 cm apart, and at the final ridging on 5 June the soil surface topography was effectively the same as in 1969 (and the same correction was applied to meter readings). The site was Xs, the access tubes were inserted about 28 May after 5 mm rain in the preceding seven days, and in the three days to the first monitoring there was only a trace of rain. The cover then was about 15%—and somewhat poorer at the future SE I site. By the end of June the cover on O sites was about 75% and, over the plots in general, somewhat more for the irrigated plants, but near the access tubes at I sites virus disease had killed several plants, with the effect more severe at the SE site, and it is noteworthy that all later readings at SE sites were rejected because of inconsistencies and anomalies in the water balance. There were two irrigations, each nominally 25 mm, monitored in totals as 37 (NE) and 41 (SE) mm. The final set of readings was taken immediately before burning off the crop.

The wet periods in July and August produced conditions that put rather too severe a stress on meter performance and there was occasional trouble with the meter itself. (It was No. 1, the first constructed and in its fifth year of use. This intermittent fault was cured by a change in the counting system, in time for work in 1969.)

A layer-by-layer diagram, corresponding to Fig. 8 for 1969, showed the same general character (with two exceptions), of apparently constant water content below 60 cm depth both at O sites and at I sites. The first exception was clear evidence of flooding at the bottom of the NW O access tube after 83 mm of rain between 3 and 26 July, with wetting from 0 to 60 cm, and no real change 60 to 120 cm at either of the O sites. In the same period, at both I sites, in all five 30 cm layers, there was apparent drying, very uniformly equal to *c*. 8 mm in each of the four 30 cm layers 30 to 150 cm, suggesting a zero shift in the meter used on the I sites, of about 2·5% in volume. These I site results were rejected as worthless and the estimate of E_I for Fig. 9, right, was obtained by setting $E_I = E_O$, with E_O based—acceptably—on the measured change 0 to 60 cm, as set out in Table 7.

The dependable part of Fig. 9, right, ends with Period 6, and the general slope, Periods 2 to 6, is near 1·05. There is evidence of an early check to transpiration (when the

https://doi.org/10.23637/ERADOC-1-7

TABLE 7(II)

Potatoes, 1968. Water balance and evaporation (mm)

	Period	R	D (O) NW	D (O) SW	$R+\bar{D}$	D (I) NE	D (I) SE	I NE	I SE	$R+\bar{I}+\bar{D}$	ΣE_T
1	31/5–7/6	8·4	2·8	8·7	14·2	5·0	3·1	—	—	12·4	19
2	7/6–14/6	2·8	5·6	5·7	8·4	−7·4	−2·2	18·2	15·6	14·9	44
3	14/6–21/6	4·6	15·0	4·0	14·1	0·7	−8·6	18·5	25·0	22·4	65
4	21/6–1/7	39·7	—	— }	—	−13·2 }	—	—	—	26·5	89
5	1/7–3/7	0·0	−3·6	3·9 }	39·9	5·5 }	−9·4*	—	—	5·5	96
6	3/7–26/7	83·0	(−17·7)	(−15·3)	66·5	27·6*	42·7*	—	—	(66·5)	156
7	26/7–5/8	7·1	—	—	—	4·3?	−15·9*	—	—	11·4	171
8	5/8–5/9	78·0	−17·3*	−27·5?	57·6	−33·9?	−9·0*	—	—	44·1	232

* Ignored

( ) 0–60 cm for O: assumed $E_I = E_O$

deficit under O plots was near 15 mm), and of an over-recovery in the wet period that followed, but though the differences involved are probably not as great as the uncertainty in measurement, the phenomenon is worth noting because it happened in 1969 too.

Beans, 1968

The beans (Maris Bead) were drilled on site Xn on 5 March at a row spacing of 53 cm. They emerged about 3 April, and the access tubes were installed about 16 May. At the first monitoring (21 May) the plants were 20 cm high and giving about 20% cover. Growth thereafter was uniform, and maximum height of 130 to 135 cm was reached by about 10 July, with 100% cover. By the end of July (Period 8) the pods were maturing and the lowest leaves on the plants were dying.

The irrigation operations were most unfortunately timed in relation to succeeding weather, the third and fourth being given at the start of the two very wet periods (7 and 9, Table 8) that produced difficulties in analysing the potato results without these extra

TABLE 8(II)

Beans, 1968. Possible water balance and evaporation (mm)

	Period	R	O D_O	O $R+D_O$	I I	I D_I	I $R+I+D_I$	ΣE_T
1	21/5–31/5	5·3	19·9	25	—	19·6	25	25
2	31/5–6/6	8·4	6·6	15	—	10·9	19	40
3	6/6–12/6	2·8	20·4	23	23·5 (Av.)	−0·2	26	60
4	12/6–19/6	2·0	18·3	20	—	24·0	26	85
5	19/6–26/6	19·0 }	−3·8	38	22·5 (SW)	−31	11	104
6	26/6–4/7	22·4 }				10	32	128
7	4/7–18/7	79·5	−53?	27?	26·6 (SW)	−67?	39?	164
8	18/7–29/7	4·1	29?	33?	—	26?	30?	188
9	29/7–27/8	60·8 }	−28?	58?	} 26·9 (NE)	−35?	78?	259
10	27/8–5/9	25·4 }						

irrigations. The analysis is thus even less satisfactory than that for the potatoes, and depends rather heavily on subjective judgements: some of the figures in Table 8, after Period 4, may be 5 or 10 mm in error, and the only minor justification for retaining those queried is that a second fresh analysis after an interval of four months produced no important change in Fig. 10.

There was very frequent evidence of flooding (and draining) round the bottom of access tubes and for nearly all entries in Table 8 the changes in layer 120 to 150 cm were ignored. At the O sites, at the end of Period 5 there was meter trouble (inferred from

https://doi.org/10.23637/ERADOC-1-7

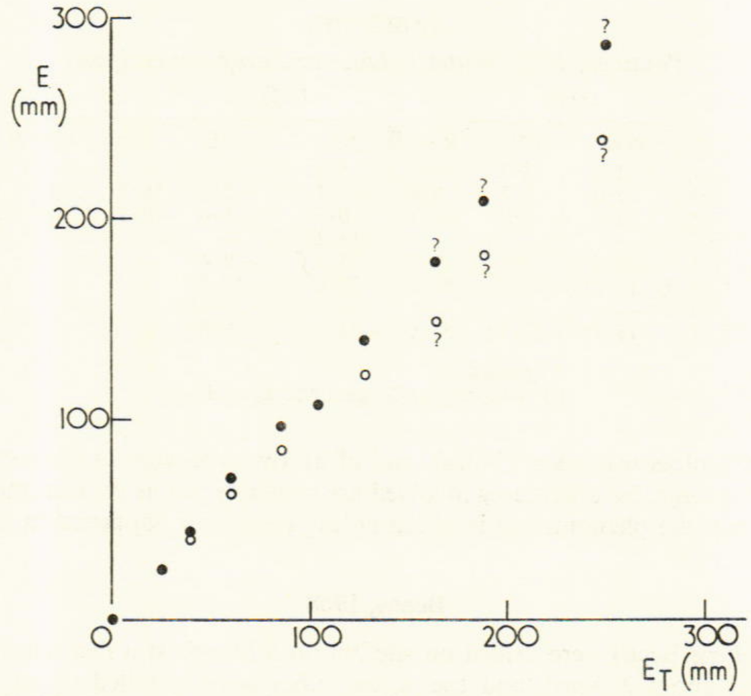

FIG. 10 (II). Evaporation from beans, 1968. Full points, I sites; open points, O sites.

inspection of profiles and their changes) and hence Periods 5 and 6 are treated as a single period. In Periods 7 and 8, the O site NE results were absurd, but those at the NW site were less suspect and these appear in the table. Periods 9 and 10 are really only a single period, split because at one I site only (SW) there was a monitoring on 27 August. As it happened, the results were untrustworthy and had to be rejected.

Elsewhere at I sites there were no serious processing problems up to the end of Period 4, but in Periods 5, 6, 7 and 8 there were flooding problems at I site NE, and only the SW site records are used, with increasing uncertainty.

The slope of a line through the points for I sites in Fig. 10 is about 1·1, and the points for O sites diverged during Period 3, at the end of which the net drying since 21 May was 47 mm. Of this 30 mm had come from the top 30 cm of soil.

Kale, 1968

The macroplots were left fallow in 1968 to permit elimination of weeds that had become a nuisance. On a site nearby, however, there was a plot of kale, 30 × 10 m, planted for a radio-isotopes experiment by the Letcombe Laboratory of the Agricultural Research Council. The intention was to irrigate half of the area, but over the relevant part of the summer the estimated soil moisture deficit did not reach the predetermined threshhold, no irrigation was applied, and so all four sites of access tubes are O sites.

The crop (Marrow Stem) was sown on 22 April, it emerged about 2 May, and, after a fortnight of heavy rain to 12 May, the plants were 2 cm tall, and cover was about 1%. The first monitoring took place on 20 June, when the plants were 25 cm tall, and covering 26% of the ground. At the second monitoring (30 July) the height was 120 cm and cover was complete, and at the third (23 August) the height was 135 cm.

There may have been a little drainage during the first period—there was some flooding

https://doi.org/10.23637/ERADOC-1-7

TABLE 9(II)

Kale, 1968. Water balance (mm)

Period	(cm)	Net drying D NE	SE	SW	NW	$\bar{D}$	R	$R+D$	E_T	$\frac{(R+\bar{D})}{E_T}$
20/6–30/7	0–120	−5·1	9·5	3·7	4·4	3·1	123	126	102	1·23
	0–150	−6·3	(9)	3·5	4·3	2·6				
30/7–23/8	0–120	−5·7	−10·0	−17·5	−11·7	−11·2	63	51	44	1·16
	0–150	−4·3	(−13)	−17·9	−11·6	−11·7				
Total	0–150	−10·6	−4·3	−14·4	−7·3		186	177	146	1·2

at the bottom of the SE access tube—but in Table 9 it is assumed that all rain stayed in the profile to 150 cm.

The scatter in the replicates is rather large, probably because of non-uniform shedding of rain around the plants and access tubes, and the best estimate of $(R+\bar{D})/E_T$ is 1·2 throughout.

https://doi.org/10.23637/ERADOC-1-7