Rothamsted Experimental Station Report for 1972 Part 2


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Water Use by Farm Crops
I. Test of the Neutron Meter on Barley, Beans and Sugar Beet, 1970

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Summary

Since 1962 neutron meter measurements have been made on the Clay-with-flints soil of Great Field, Rothamsted, with irrigated sites included from 1964 onward. At first the depth range was from 0 to 90 cm; later, it was 0 to 150 cm, still perhaps not deep enough, but even this was achieved only with great difficulty because of the flints. Using a 200 mC source (Americium 241/Beryllium: details in Long & French (1967) *Journal of Soil Science* **18**, 150) the precision was adequate (to about 1 in 400 in volume concentration), and Part I of this report is a detailed attempt to seek circumstantial evidence of accuracy from measurements made under three crops, irrigated (I) and unirrigated (O), on the site in 1970. Field calibration is impossible, and laboratory calibration cannot include field factors that dominate meter response to changes in water content. After allowing for a small background count the volumetric water content θ cm° (i.e. cm^3/cm^3) at depth z is n/N, where n is the measured count and N is the corresponding count in water at the same depth below a water surface. Below $z = 20$ cm, N is constant. In study of ten years' records there has been no occasion to suspect the reliability of n/N in estimating changes in water content. Over a layer of soil profile the water content, δW, is $\sum\theta\delta z$: in measurements, $\delta z = 5$ cm, 0 to 30 cm, and $\delta z = 10$ cm, 30 to 150 cm. A change in total from W_1 to W_2 represents a net drying D, given, in its most general form, by

$$D = W_1 - W_2 = E + d - (R + I),$$

where E is the evaporation, d is the drainage below 150 cm, R is the rainfall, and I is the irrigation. The main test of the instrument is that when d is zero or negligible, and there is good reason to suppose that $E_O = E_I$, then $D_O - D_I$ should equal I, the irrigation applied. Uncertainty in D is about 2 mm for a period of about a week, and in I it is about 3 mm in a total near 30 mm. (The difference between the measured I, monitored at an access tube, and the nominal I, measured through a water meter, can exceed the difference in water use between O and I treatments.)

Most field uncertainties stem from (a) the short range of sensing by the meter (most of the response depends on conditions within a few centimetres of the access tube); (b) the unavoidable gap between the outside of the access tube and the soil around it. Distortions can arise from (a) plant roots growing into or close to the gap; (b) plant spacing being so great (e.g. sugar beet) that only one (or at most two) plant(s) can affect response; (c) the gap may be flooded—and remain flooded for several weeks in the clay soil of the site; (d) non-uniform shedding of rain or irrigation water; (e) (considered in Part II) the first severe drying of the summer causes shrinkage in the top soil layer and apparent drying is greatly exaggerated. Some of the distortions are self-correcting in time, and replication can do some smoothing, and help in quality control.

For the *meter*, duplicate results under barley agreed well and tests of the equation (above) were satisfactory. Duplicate measurements under beans were nearly as good, but the balance equation could not be applied. Quadruplicate measurements under sugar beet were very erratic, but averages, after quality control, were coherent. The meter

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seems to be accurate, and, thoughtfully used, is a good research tool, but is not ready for routine use.

For the *crops* a long period seasonal water balance is made in terms of total measured evaporation, E, plotted against total estimated potential evaporation, E_T, up to the same epoch. At I sites, the points lie on straight lines (slope κ) in the main growing season of full cover. At O sites, the points, in general, coincide with those for I sites for some time and then may diverge in the sense that $E_I > E_O$. For barley in 1970, the divergence occurred when the soil moisture deficit under the O plants was $D_O \simeq 135$ mm, and at harvest $E_I - E_O \simeq 25$ mm. For beans, $D_O \simeq 50$ mm, and at harvest $E_I - E_O \simeq 90$ mm. For sugar beet a divergence began immediately after the first irrigation (soon after singling) and continued after the second, but thereafter there was no distinguishable difference in the values of κ: much of the extra evaporation was from the wet irrigated soil before complete leaf cover was established.

For the *soil*, the concept of field capacity is of very little value. There are suspicions (no more) of slow drainage from the soil profile, and near certainty that the crack system in the clay permitted penetration of water without complete re-wetting of all the soil that it had passed: it is assumed that the effect did not extend beyond the 150 cm depth of monitoring. At its wettest, the water content of the soil profile, 0 to 150 cm, differed greatly within a total area of *c.* 200 × 200 m. Sixteen sets of measurements had a range from 610 to 750 mm, with an average of 670 ± 50 mm. The range for all sites at wettest is about the same as the biggest net drying measured at any one site. In this soil, sampling is not a way to calibrate a meter.

Introduction

Since 1964 there has been an irrigation experiment on Great Field, Rothamsted, immediately to the west of the meteorological enclosure (Fig. 1). The practical objective (not to be considered here) is to measure crop responses to irrigation, as a supplement to 20 years' experience on a sand soil at Woburn, 35 km away (Penman, 1962, 1970, 1971). The secondary objectives include an attempt to interpret the seasonal history of growth and development in terms of physics and plant physiology, and to this end the experiment is designed to measure everything possible in the physical environment of the growing crop, plus many relevant botanical measurements. In this context the irrigation, in summers dry enough for it to be needed, is simply a method of imposing a contrast in environment. Nearly all of the elements are recorded several times per hour, and a change to automatic sensing for computer processing was started in 1970, with the effect that very nearly all of the routine recording of temperature, humidity, ventilation, radiation, carbon dioxide concentration—and so on—had to be omitted. The routine maintained was the measurement of soil water content, from the surface to 150 cm depth, using the meter assembly based on neutron scattering (Long & French 1967; this will often be shortened to L. & F. in what follows), supplemented by markings of the state of the crop (stage in development, height, fraction of ground covered, leaf area index). Measurements were made at roughly weekly intervals, under three crops, irrigated (I sites) and unirrigated (O sites), and, including replicates, 268 profiles were measured during the summer.

It is convenient to use the 1970 results as an exhaustive field test of meter performance, to show what it can do, the nature of the uncertainties and variance that appear in the readings, and to look at ways in which the results can be expressed, either as a guide to quality control or for interpretation. Starting with later experience will help in detection of possible deficiencies in technique in previous years: it will soon become abundantly clear that this is still a research tool, not yet ready for routine use in untutored hands.

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A good instrument has to stand up to at least three criteria. Is it reliable? Is it precise? Is it accurate? The third question is the subject of the present paper, so the first two need only brief answers here. As built (L. & F.) the meters (two were used in 1970) were always ready for use when wanted, a condition dependent on having the necessary skill to detect when something might be going wrong, to diagnose the trouble, and to cure it, backed by suitable laboratory facilities for testing and servicing.

Evidence of precision will appear in many of the diagrams, but some numbers now may help. The two meters differed in sensitivity, but for the weaker of the two it was possible to reproduce readings to within a few counts in 20 000. In converting to water content a third figure was retained with no feeling of absurdity, i.e. absolute water contents are given to one part in about 400. This degree of precision is very desirable. All important decisions have to be based on first differences, and many depend on second differences, so adequate precision in the primary records is essential. As an example: at one time the water content of some of the profiles examined might be near 600 mm as rainfall equivalent, and after a week of fine weather it might decrease to 580 mm. At another site the corresponding change might be 700 to 675 mm. The first differences are 20 and 25 mm respectively: the second difference is 5 mm, but even with the precision used here it might be 5 ± 2 mm. Does one crop use water more rapidly than another? The field answer will depend on such second differences. In the limit, the precision probably depends on the observer and not on the instrument. A stop-watch and an electronic counter are started and stopped together (left hand and right hand pressure on button and switch) for an interval of 100 seconds. The total timing error in the two simultaneous operations should not exceed one-fifth of a second, or one part in 500 in the count rate. This corresponds to about 0·001 in volumetric water content, or, when used as a representative value for a soil layer, to 0·1 mm in the water content of a layer 10 cm thick.

The site

Great Field (10 ha in total area) is bounded by lines of tall trees on west and south sides. Formerly it was in two parts, separated by a hedge, and there were occasional trees in the hedge line, and even in the 'fields' themselves. The clearance took place many years before 1964, but in laying out the irrigation experiment the old hedge line and old tree sites had to be avoided, and as large as possible an area left between the site and the bordering trees. To achieve any worthwhile agricultural meteorology in transfer processes the plots needed to be large, and hence only three blocks could be fitted in. As these will be referred to frequently, a code will assist in identification.

To the west are two blocks (Fig. 1) Xn and Xs, that carry conventional irrigation experiments every year, i.e. with replication, and randomisation of water and other management factors, and the main plot size (as for irrigation) is about 35 × 30 m. On each block there are four access tubes, two on unirrigated plots (O sites), and two on those irrigated plots planned to receive maximum watering during the summer (I sites). These are installed outside the part of the block to be harvested for yield, and code symbols NE, SE, SW and NW show their relative positions. The eastern part of the area contains only two plots, Mn and Ms, each 92 × 92 m, the so-called 'macro' plots that receive identical treatments except that one is irrigated and the other is not. These are the sites of the agricultural meteorology and crop physiology every year (except 1970), and they carry four access tubes each. To the east of the Mn plot is the meteorological enclosure, and on the south side of this is the field laboratory housing the recorders linked by cable with the many sensors above, in and below the crops on areas Mn and Ms.

The old hedge line runs east–west between the north and south groups of plots, and the buried main bringing in the water is on the same line.

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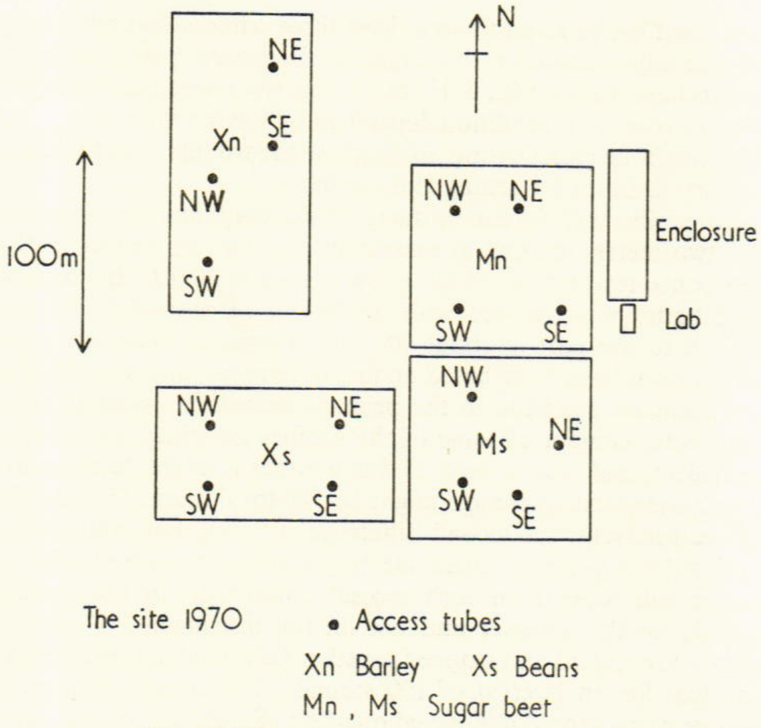

FIG. 1 (I). The site, Great Field, Rothamsted.

The soil, at least in the plough layer, is Clay-with-flints, and has one major attribute important in farming on it. There is shrinkage and cracking on drying, and the swelling on re-wetting is very slow, so that only after an exceptionally long winter period of wet weather do the fissures close enough to impede drainage. In summer, as will be discussed later, the fissures may expedite drainage and possibly produce anomalous impressions of water balance.

Below plough layer, almost anything can be found. The Clay-with-flints may persist, with the large flints scattered, or with small ones packed into a tight layer some 20 or 30 cm thick. Getting a clear run with an auger is a rare event, and after many failures the acceptable best may involve pushing one or more flints (*c.* 100 cm^3 or more) aside in the process. In places the underlying chalk is close to the surface, and the auger may move into the clay/chalk brash at the transition; at one site (Xs, SE) the auger almost reached solid chalk at 150 cm. In at least one place (Ms, SW) there is a sand lens (horizontal extent unknown). Adding to these factors possible disturbance produced by former shrub and tree vegetation, it will be seen that there is no such thing as 'the' soil profile: at each monitoring site that is 'a' soil profile, and 16 versions of it appear in Figs. 2, 9 and 14, in terms of changes of water content, near saturation, with depth.

The instrument

Details are in L. & F. (pp. 149–153). There are two sources and meters, using Americium 241/Beryllium, 200 mC, that produce 4·6 and 6·5 $\times$ 10^5 neutrons per second, i.e. both meters are much more powerful than any commercial assembly. The detector is BF_3. Although these components are as small as possible, in their protective aluminium case they are far from being the ideal 'point' assembly: the case is 170 mm long, and 34 mm in outside diameter, and is at the end of 2 m of suitable cable. The aluminium access

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tube has inside and outside diameters of 35 and 38 mm. The meters used in 1970 gave 100-second counts of 25 500 (Meter 3) and 42 900 (Meter 4) in water.

In their laboratory calibration (L. & F., pp. 153–159 and Fig. 5), Long and French packed two deep layers of uniformly wetted Rothamsted soil round an access tube, keeping the lower one constant and changing the upper one through a range of dryness down to zero—air only. They found, as others have done (e.g. Perrier & Johnston, 1961), that in going through a discontinuity at an interface there is no abrupt change in meter reading: a detectable change (about 1%) starts 15 cm from the interface, and the reading passes through the average reading near, but not at, the interface. The response curve is not symmetrical about the interface, but is very nearly so about the average value, which is reached on the wetter side of the interface by a distance that increases with the contrast in water content across the interface. At the extreme, for soil at 0·53 cm^3 per cm^3, to air, the reading is 0·27 cm° at about 3 cm below the soil surface. The sigmoid shape of the response curve will persist to some extent in real soil profiles with non-uniform water content, and though there is no reason to doubt the reliability of integrated water contents, it is very doubtful whether reliable gradients of water content can be inferred from measurements. This is a limitation that has to be accepted, but is no worse than a curb on utility. In effect, the sensor system is responding to water within 15 or 20 cm of it, above and below the level of monitoring: what is more important is the horizontal range to which it is responding, and the relative contribution of successive cylindrical shells around the axis of the access tube. Measurements by McHenry (1963) in water, around an access tube, indicate that the slow neutron density in the water is approximately spherically symmetrical about the source as centre, and because the density decreases very rapidly beyond 2 or 3 cm away from the source, the response of the sensor in soil may be almost completely dependent on the water content of the soil within a few centimetres of the outside of the access tube. This is the region in which any uneven packing on installation of the access tube could produce misleading results, and the same kinds of distortion could occur by shrinkage of a clay soil, or by accidental flooding, from rain or from irrigation water, or by uneven root distribution producing preferential drying close to the access tube. No laboratory calibration, however thorough, can take care of behaviour of this kind, and as there is no method of field calibration available, all field readings need careful scrutiny before acceptance.

Field installation, 1970

Sixteen access tubes were inserted, under three crops: four in each macro-plot (sugar beet) at I sites, Mn, and O sites, Ms; two each in O and I sites Xn (barley); and two each in O and I sites Xs (beans). All were placed in plant rows, using the following method.

Augers and reamers were used, increasing the length as needed. As soon as the soil was dry enough to walk on after the emergence of the crop, an auger, 32 mm outside diameter, was used to drill a vertical hole about 20 cm deep. If flints were encountered the site was abandoned and another tried, at least a metre away. When the first stage was successful a mild steel reamer, outside diameter 38 mm, inside diameter 34 mm, followed, enlarging the hole. The auger was then screwed into the reamer, first to remove the soil in it, and then to open the next 20 cm of pilot hole: the reamer was then forced further down. As this second stage became more difficult the reamer was withdrawn, cleaned inside by the auger, and outside by a wet cloth, the water acting as a lubricant on re-insertion. When flints were encountered below 20 cm but were pushed aside by the auger or brought up in the reamer, the hole was considered fit to use, but if flints deflected the auger and damaged the wall of the hole then the site was rejected and a new one sought at least a metre away. This often occurred. The final satisfactory depth was 160 to 162 cm,

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leaving a little space below the access tube (160 cm) to accommodate any soil that might be pushed down ahead of the tube when it was pressed into the hole. The final stage of insertion often needed heel pressure. The surface soil was then pressed firmly into position, with the top of the tube at the same level. Footprints around the site were then lightly forked out.

The access tube was sealed at the bottom by an aluminium plug (10 mm) cemented in, and, between observations, closed at the top by a rubber bung. The top was the reference level for all measurements, and on a few sites soil shrinkage caused it to project a few millimetres above average soil level in late summer: in the sugar beet the swelling roots forced the soil a little above the top of the tube. (This relative movement at the surface is negligible in its effect on estimation of changes in water content.)

The coaxial cable was marked off in 5 cm divisions measured from the middle of the probe as zero—the position of the source and of maximum sensitivity of the BF_3 detector tube. The markers were built up as collars, big enough to catch on the lip of the access tube, so every time the probe was lowered it was always at the same chosen level relative to the top of the tube. The cable expanded with temperature (3 mm in 150 cm at the most), and new cable shrank on ageing (again, *c.* 3 mm).

Technique. Before starting in the field, the meter was switched on with the probe in its wax container to check correctness under fixed conditions. Then, at the end of a handling tool (*c.* 1 m), itself at arm's length, the probe and meter were taken on site. A fast neutron detector badge, worn by the operator, was checked every month: the radiation dose received was always well below the approved safety limit. At each level of monitoring the counter switch (right hand) and stopwatch (left hand) were started together and halted after 100 seconds. The intervals were 5 cm, 0 to 30 cm depth, and 10 cm, 30 to 150 cm depth, and at least one reading was repeated. As a further check the readings were immediately compared with those at the previous monitoring and on any suspicion of inconsistency the doubtful readings were repeated. At about weekly intervals, four sites per day per meter were monitored by two observers, starting at the same time of day, and following the same order of sites throughout the season. (The evaporation during the working day could be 10–15% of the total for the preceding—and following—period.) The average time per profile was about 50 minutes.

To remove the tubes at the end of the season the soil around them was dug out to 30 cm or so. The rubber bung was replaced by a firmly fitting metal plug, and, over a thick layer of wrapped plastic tape a collar, with two hand grips, was clamped on the top of the tube. Rotation of the tube broke the contact between soil and tube and, with some considerable effort the tube was hauled out. Those in barley and beans were taken out on 15 September, and at all four sites that had been irrigated there was standing water at the bottom of the holes: there was no water in the holes at unirrigated sites, nor at any of the eight sugar beet sites when their access tubes were lifted in mid-October.

Count in water. In the meteorological enclosure there are cylindrical tanks set in the ground with rims a little above soil level. They are 2 m deep and 76 cm diameter. In one, filled with water to the brim, an access tube was clamped at the centre with 30 cm projecting above the surface. At the beginning of the season, and occasionally during it, counts were made at 5 cm intervals, as in the soil, to give the quantity N of a later section. The count became constant between 15 and 20 cm (L. & F., Fig. 3).

Miscellaneous aspects. The first circuit of the scaler was modified and a correction for 'dead time' is now needed only for Meter 4 at the most rapid count rates (see L. & F., Fig. 2).

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The background count (b of the later section) was obtained by suspending the probe about 2 m clear of the ground. Average values were 60 per minute (Meter 3) and 100 per minute (Meter 4).

There are a few precautions desirable. The meter should not be exposed to direct sunlight for long periods: over-heating may occur. Usually it will be shaded by the crop, but it is prudent for the observer to sit so that his shadow falls on the meter (and this makes it easier to read the counters). Plugs and sockets must fit tightly: loose connections produce extra counts. Care is needed in a wet crop or over wet soil: water in cable connections, on the probe, or actually inside the meter, has been the source of spurious counts.

Irrigation. When needed, water was applied via oscillating spray lines with a throw of about 7·5 m in still air. A commercial water meter measured the total volume applied to an area known only approximately, and the 'nominal irrigation', as a depth, is the ratio of volume to area. The actual depth varies greatly from place to place, and though this matters little in studying crop responses, it is unacceptable in a study of soil water balance.

Around each monitoring site five collectors were set at random radial distances between 0·5 and 1·5 m, mounted on extendable supports so that the rims could be kept just clear of the top of the crop. The positions were unchanged during the season. The collectors were plastic funnels 11·5 cm in diameter discharging into cylinders 12 cm deep and 9 cm diameter. Two sets of results in Table 1 are typical of all eight sets in 1970: the standard deviation is usually close to 10% of the average, within a range from about 3 to 16%.

Estimation of water content

At all depths below 20 cm the calculation is simple. If N is the number of counts in a standard period in water, and n is the corresponding number at depth z in the soil, then the volumetric water content at z is $\theta = (n - b)/(N - b)$ cm°, where b is the background count, of order 100 when $N \simeq 40\,000$ and $n \simeq 10\,000$ to $20\,000$.

Above 20 cm there is some complexity. The response of the meter in a uniform profile decreases toward the surface and there is a slight difference between 'water' and uniformly 'wet soil'. In soil (Fig. 3 in L. & F.) the ratio $n/N_{\max}$ for $z = 0$, 5, 10, 15 and 20 cm changes through 0·20, 0·78, 0·93, 0·99 and 1·00, respectively, whereas the corresponding values in water are 0·14, 0·70, 0·94, 0·99 and 1·00. Generalising these as a_1 to a_5, one estimate of water content at a given level is $\theta = (n - b)/aN$. This is the simplest way to calculate θ and is used in all that follows, but there is another that may be slightly better even if only because it puts a little less weight on the meter reading at $z = 0$. In a uniformly wet profile all of the five values of $(n - b)/aN$ should be the same. They never are, but a weighted average could give a good estimate of the average water content of the top 20 cm of soil, giving the smallest weight to the surface reading. The simplest weighting system is to use a_1 to a_5 as weighting factors, and then the total estimated water content (in mm) of the top 20 cm is simply $\sum W = 200\sum n/N\sum a$.

Thirty comparisons of period changes in water content, 0 to 20 cm, for the unirrigated barley (1970, O sites) showed only two in which the two methods differed by more than 2 mm, there were a few differences between 1 and 2 mm, and most agreed within a few tenths of a millimetre, with no systematic trend. Accepting the accuracy of the meter (yet to be established) the truth may lie between the two estimates: for reading the 0 to 30 cm sections of Figs. 4 and 5 it is sufficient to note that choice of the alternative method of integration over the first 20 cm might have altered the relative positions of consecutive points by an amount less than the size of the symbol used to locate a point.

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Field capacity. First attempts at analysis tried to identify a profile of water content to be used as a datum from which all changes could be measured, decreases to be regarded as deficits that must be made good by added water before there was any surplus of water to percolate to a lower level and ultimately lost as drainage when it passed below the deepest level of measurement. The effort was futile, for two reasons. The first, general, is that in any soil near field capacity there will be a slow downward movement of water, probably because of daily and seasonal changes of temperature. So an August field capacity may be smaller than that in May, perhaps by an amount of order 10 mm, or about 3% of the total evaporation in a summer's plant growth. The second, particular, but not peculiar to this soil, is that where there is enough shrinkable clay in the soil texture a system of cracks and fissures is produced on drying, supplemented by old root channels. These cracks, produced immediately on drying, do not close immediately on wetting: Emerson (1955) found that dry clods, slowly wetted, drop by drop at the top, began to drip from the bottom after a few days but continued to take up more water for several weeks. For slow wetting of a dried profile—as by gentle rain—the amount retained during the few hours of rain will be smaller than it would be after weeks of the same treatment, the surplus can move downward more rapidly because of the shrinkage cracks, and hence the depth wetted will be greater than expected on the basis of a spring value of 'field capacity'. This is often observed, and it may appear as a contrast between duplicate profiles. There is a good example on Fig. 7, Period 13, where the major wetting of the SE profile is at the top, but that of the SW profile is much deeper: it is impossible to believe that the top 60 cm of this SW profile were brought to 'field capacity' and then dried to the state as measured on 11 August. (This is only one example to justify the use of the word 'futile' in the introductory discussion of 'field capacity'.)

Under intense rain, or irrigation, behaviour is certainly more erratic, and unpredictable. Water may pass so quickly down through the fissures that it has time to do little more than wet the outsides of the structural aggregates, particularly in the upper part of the profile. This behaviour is detectable even on the uncropped and undisturbed soil (Penman & Schofield, 1941) of the nearby drain-gauges. During heavy rainfall, eventually to total R and produce total drainage d, it is possible to detect the first arrival in the drainage collector before a total of rain equal to $R - d$ has fallen. The same effect must occur more frequently and more severely when irrigating a cropped soil, i.e. the amount of irrigation water retained in the root zone will nearly always be less than it would have been if it had been applied slowly, and occasionally some will pass beyond the depth of monitoring even when the deficit at the time of irrigation seemed to be big enough to ensure retention of all that was applied. Much time has been spent in trying to interpret profile water balances in periods after irrigation in terms of departure from field capacity. Results were chaotic, with no sort of coherence between replicate profiles under the same treatment: the most that can come out of the measurements bounding such a period is the sum of evaporation and drainage without any possibility of making a partition. Fortunately, under the barley in 1970 this happened in only one of the five irrigation periods, and the other four are sufficiently free from doubts to provide strong circumstantial evidence of the accuracy of the meters.

The water balance of a profile. If θ is the water content of the soil at any level z, expressed as a volume fraction (cm^3/cm^3 or cm°) then the total water content to a depth z is

$$W = \int_0^z \theta dz. \qquad 1, \mathrm{I}$$

The instrument limits z to 150 cm, and though for a special purpose it may be desirable

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to treat a measured profile as continuous (as in Fig. 3) for more rapid survey it is convenient to work in terms of five discrete layers each 30 cm thick. For the bottom four, with readings at 10 cm intervals, estimation is simple. There are four readings: θ_1 (top); θ_2 and θ_3 (middle); θ_4 (bottom). Leaving these as percentages, then

$$W = \tfrac{1}{2}(\theta_1 + \theta_4) + \theta_2 + \theta_3 \text{ mm.}$$

For the top layer, with seven readings at 5 cm intervals $W = \frac{1}{4}(\theta_1 + \theta_7) + \frac{1}{2}\sum_2^6 \theta$ mm. The method is quick and generally accurate enough: on rare occasions on which inferences are questionable profiles can be plotted in detail to see if the layer-by-layer treatment has introduced distortion. Then, with n taking values from 1 to 5, the total water content is

$$W = \sum W_n.$$

If over a period it changes from W_1 to W_2 then

$$\begin{aligned} W_1 - W_2 &= E + d - (R + I) \\ &= D \quad \text{say,} \end{aligned} \qquad 2, \text{I}$$

where E is the evaporation, d is the drainage, R is the rainfall, I is the irrigation, and D is the net drying of the profile. With no irrigation,

$$D_O = E_O + d_O - R. \qquad 3, \text{I}$$

With irrigation,

$$D_I = E_I + d_I - (R + I). \qquad 4, \text{I}$$

Now consider conditions in which d is negligibly small, or in which $d_O = d_I$. Using the subscripts now as treatment labels then

$$D_O - D_I = (E_O - E_I) + I, \qquad 5, \text{I}$$

and over a period in which the irrigation treatment is zero, then the difference between the estimated values of D is the difference in evaporation from the two kinds of treated plots. When there is reasonable expectation that $E_O = E_I$, then $D_O - D_I$ must be zero, and a test that this is so is a necessary, but not sufficient, test of the accuracy of the instrument. A much more searching test is possible when there is irrigation applied (and strong presumptive evidence that it has all stayed in the profile), and when the same assumption about equal evaporation can be accepted. Then the estimated value of $D_O - D_I$ should be equal to the amount of irrigation applied.

The precision of the measurements is such that D can be expressed to the nearest millimetre, i.e. there is a possible uncertainty in $D_O - D_I$ of about 2 mm. This is close to the value of the standard deviation in the measured estimate of I (Table 1), and is about 10% of the evaporation in most of the periods examined: it will be very acceptable to get evaporation estimates over short periods agreeing as closely as this for duplicate treatments. As it happened the values of D_O for duplicate plots of barley in 1970 agreed exceptionally well in nearly all periods (Fig. 6), and hence the derived pairs of values of E_O were nearly always identical, but this is no more a virtue of the meter than expected scatter is an indication of inaccuracy. So, in periods when E may be from 10 to 30 mm, the errors in processing (to get D), differences between sites (producing differences in E for duplicate treatments) and experimental scatter in the estimation of I, all have uncertainties of 2 or 3 mm. Nearly all of these are random so that accumulated values of E_O and E_I should become more and more exact as the time interval over which they are integrated increases. For most crops in most summers the final value is near $E = 300$ mm. Some inaccuracy in the meter will not seriously affect comparisons of E_O and E_I or decisions about when they first begin to differ, but in comparisons of each of them with a

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prediction formula (Fig. 8), or with indirect estimates based on contemporary meteorological measurements (for a later communication), the accuracy of the meter is all-important.

Barley, 1970

The crop (Zephyr) was drilled on 20 March at 18 cm row spacing on site Xn. Two weeks after emergence, on 28 and 29 April 1970, access tubes were inserted in the rows at about 16 m in from the edges of the barley area, NW and NE for the O sites, SW and SE for the I sites (later to be irrigated). The first profiles of water content were measured on 4 May a few days after rain (22·6 mm, 25 April to 1 May): except for slight drying near the surface the profiles would be near 'field capacity' as usually defined. The crop grew well, with no obvious differences around the sites of the access tubes. Instructions for irrigation were to try to keep the soil moisture deficit on I plots near or less than 25 mm:

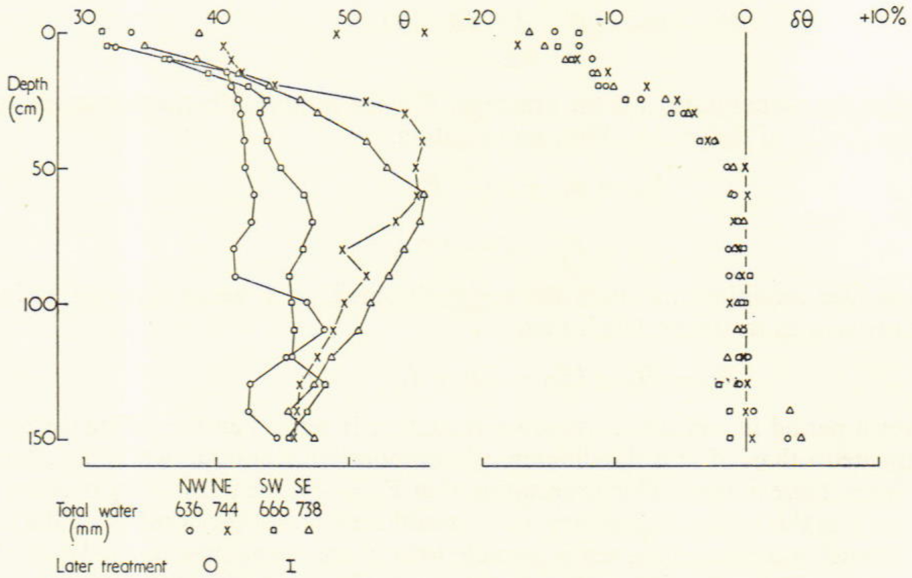

FIG. 2 (I). Left. Water content profiles under barley, 4 May 1970. Right. Changes in profiles, 4 to 26 May, before any irrigation was applied.

there were six applications (Table 1). Ear emergence occurred about 12 June, i.e. during period 6, and soon after the second irrigation there were detectable differences in crop appearance. By 10 June there was a measurable small difference in leaf area (I > O), and a week later a similar difference in crop height (at the maxima, $h_I \simeq 98$ cm; $h_O \simeq 88$ cm). By 17 July all the O site plants had turned yellow, but it was 10 days later before all the plants on I sites had changed colour. Harvest was on 12 August, preceded by a set of readings on 11 August, and there were two further sets of readings before the stubble was ploughed. At harvest there were a few weeds in the stubble of the O plots, and many more on the I plots. Rain after harvest produced an almost complete weed cover on all the area.

Profiles, 4 May 1970 (Fig. 2, left). There are now many sets of such profiles, some showing even wider contrasts than these four. The integrated values have a range from about 635 to 740 mm of water in a depth of 1500 mm of soil, i.e. the average (if it has any meaning) is from 0·40 to about 0·50 by volume. Lawes and Gilbert, in their very laborious sampling 100 years ago (at one site close by) got a value of 0·30 down to *c.* 25 cm, and,

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roughly, 0·50 from 25 to 140 cm (Penman & Schofield, 1941; Table 4). Lawes and Gilbert may well have got the right answer, and might have got a very different and equally correct answer at another site only a metre away. On-site soil sampling is no way to calibrate a moisture meter in this soil, and an early attempt to do so (1964) was given up when 100 samples had done no more than show the variability of soil water content at short distances from a chosen point.

At this stage absolute accuracy is unimportant: in all applications envisaged it is a change that is important, and with four such very contrasting data to start from the neutron meter is being put through a somewhat harsher test than it would get in a soil with less severe and more uniform changes in texture with depth.

Profile changes, 4 to 26 May 1970 (Fig. 2, right). Measurements were made on 15 and 19 May, but it is useful to look at the whole period for which all four holes are replicates, i.e. before any irrigation was applied. In this three-week period the crop height increased from about 10 cm to almost 30 cm, and from the evidence now to be discussed the deficit increased by *c.* 42 mm, there were 17 mm of rain, and hence $E \simeq 59$ mm for the period.

Fig. 2 gives the four individual values of $\delta\theta$ at each of the levels of observation, and, except in the top 5 cm, and the bottom 10 cm (a special problem, considered below), the agreement is impressive. A mean line, if drawn, would be significantly displaced to the drying side of zero between about 60 cm and 130 cm, and uniformly so. Here arises, for the first time, the question that persists through all this analysis. Is this deep drying the result of plant root activity, i.e. to be credited to 'evaporation' in a water balance sheet, or is it drainage? From the appearance of the difference profile few would dispute that it is drainage, and though this will be accepted here, it is simply an opinion.

Four curves of $\delta\theta$ against z could be drawn, but, instead, their integrals are given in Fig. 3, in two ways. For the O sites the individual points represent

$$\int_0^z \delta\theta dz,$$

i.e. the total drying down to depth z in the profile. The full line drawn is the mean of the two. For the I sites this full line was used as datum to estimate the difference between the

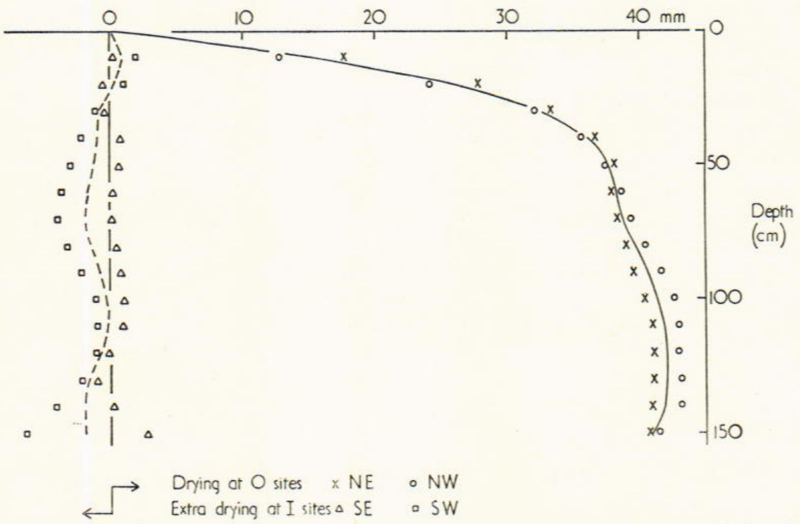

FIG. 3 (I). Accumulated drying, 4 to 26 May. Full line. Average D_O for future O sites. Dashed line. Average $D_I - D_O$ for future I sites.

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net drying at the O sites and at the I sites, and, as a visual aid, the difference is plotted so that extra drying at the I sites is represented to the *left* of the zero line. This double sign convention (not to be used again) has the immediate advantage that, in terms of means, the net drying down to any level for O sites is the displacement of the full line to the right of the zero line, and for the I sites it is the displacement of the full line to the right of the broken line.

Only a few points of interpretation need to be set down. First, more than three-quarters of the net drying occurred in the top 30 cm, and the mean for I is only 1 mm more than the mean for O. Most of what is certainly plant root activity occurred in the top 50 cm, affecting meter readings down to about 70 cm. Below (O sites), as mentioned already, the further drying of about 3 mm may well be drainage. Between 70 and 110 cm the mean I curve is almost parallel to the mean O curve, i.e. these plots behaved in the same way, with perhaps 1 mm more of drainage. Behaviour in the lowest 20 cm is to be ignored, for a reason now to be given.

A major defect in the technique. Of the neutrons that return to the detector nearly all suffer their retarding and deflecting collisions within a few centimetres of the outside of the access tube. If a particular layer of soil has a uniform water content in the horizontal this causes no trouble, but if there is any differential wetting (or drying) close to the access tube then readings will be distorted upward (or downward). For an access tube rather slackly inserted in the soil these distortions may be very large, necessitating a correction. In the 1970 work there was no suggestion of any need for this kind of correction, and it will not be discussed until its importance is demonstrated, but even the closest fit attainable leaves some small air gap between tube and soil. Occasionally, and more often under irrigation, this gap will be flooded, and depending on how much the soil was puddled in excavating the hole for the access tube it may take several days—perhaps weeks—before this surplus water either drains away downward or is taken up sideways into the soil alongside. The effect on period differences goes both ways, probably well represented in Fig. 3. When the period starts with a flooding that disappears, the drying will appear excessive (SW points?) when the period ends with a flooding the wetting will

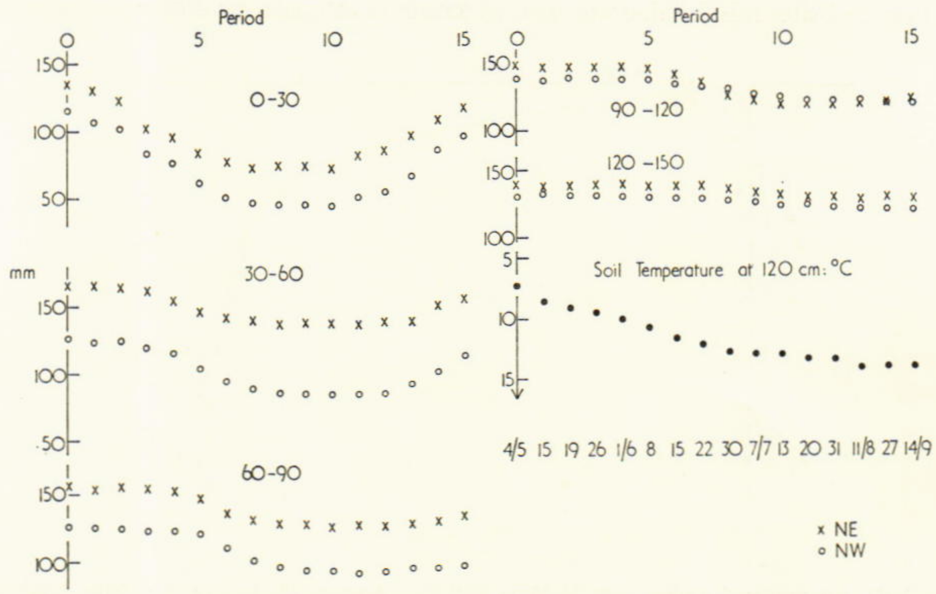

FIG. 4 (I). Seasonal changes in water content, by layers, under unirrigated barley, 1970.

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appear excessive (SE points?). The effect is usually easily detected (examples will be pointed out later), and it rarely affects more than the bottom 30 cm of the profile: for some water balances it may be necessary to ignore this layer.

Seasonal changes by layers (Figs. 4 and 5). There were 16 sets of measurements, approximately at weekly intervals, so providing 15 periods. For the present it is sufficient to consider only the historical sequence.

***O sites* (*Fig. 4*).** The changes in total water content (mm) are plotted for both tubes for the five 30 cm layers. Down to 120 cm there is no doubt that the increasing dryness is the result of root action: the decrease of 10 mm in the deepest layer may represent slow drainage, and, if so, it will be an under-estimate of the total slow drainage from all the profile. Note that in all layers the water content tends to a constant value, reached later the greater the depth, and that if the maximum decrease is identified as the 'available water' (at least for the 0 to 30 cm layer) it is greater for the profile that starts with the lesser amount; this difference is common to the first three layers but not from 90 to 120 cm. Here it is possible that some roots got into the space between soil and access tube of the NE profile, producing some differential drying and exaggeration of the drying.

As an indication of precision, it is worth noting that a point in these sequences that is out of trend by more than 1 or 2 mm may represent faulty arithmetic, and a check is desirable.

***I sites* (*Fig. 5*).** The corresponding diagram is much more compressed because the irrigation kept the water content of the profiles almost constant. In the upper layers the generally smooth trends of Fig. 4 do not appear in Fig. 5 because of the irrigation, and because the amounts of irrigation received at each access tube were not the same (Table 1). Down to 90 cm there is no obvious reason to doubt the reliability of any of the measurements: below, there is. For 120 to 150 cm, only the first three readings may be acceptable (the first of all has already been doubted), and in Period 4—the first irrigation period—

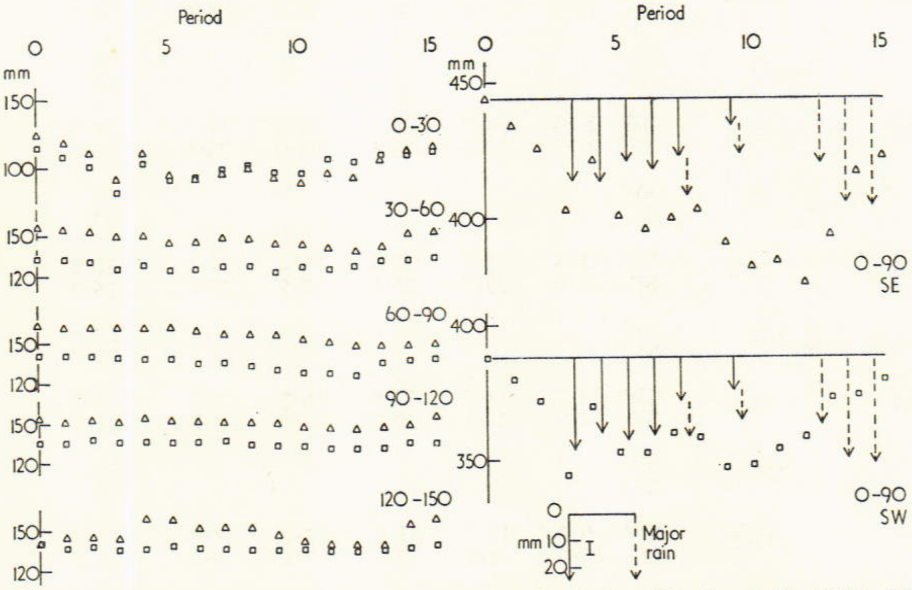

FIG. 5 (I). Left. Seasonal changes in water content under irrigated barley, 1970. Right. Changes, 0 to 90 cm, and applied irrigation and major rain, on more open scale.

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the great increase is almost certainly caused by flooding round the bottom of the access tube, an effect detectable in the 90 to 120 cm layer too. The water may have drained away or been absorbed by Period 10 but there are the same symptoms in Period 14 and again in Period 15. The detail for Period 14 is in Fig. 7, and for hole SE the apparent gain in water in the whole profile exceeded the rain that fell by 1·5 mm. Here the meter is obviously grievously inaccurate—if the readings are accepted without discrimination. How to discriminate must involve subjective judgement, and though judgement here is easy—reject all the SE readings 120 to 150 cm—there will be marginal cases in which there can be no more than suspicion of error and readings have to be accepted as they emerge from the processing.

Figure 5 gives no indication of through drainage, but it is noteworthy that the trends of drying in the 90 to 120 cm layer are very much the same as for 120 to 150 cm for the O sites (Fig. 4), and the drying of the 90 to 120 cm layer (of about 7 mm in total) may represent slow general drainage from that layer. There is good reason to infer that the root activity of the barley on these irrigated plots was limited to a depth of less than 90 cm (Russell, 1971, his Fig. 7.2, shows there are very few roots beyond 60 cm). As a supplement, Fig. 5, right, gives the integrated values of water content to 90 cm, with amounts of irrigation and of major rain represented by vertical arrows starting from the wettest state measured at any time during the summer. (It happens to be at the first observation.) This datum may not be field capacity, but it will be very close to it, and, as indicated, it may not be constant during the summer, and allowance for a possible decrease will enhance the value of the argument that follows. When an arrow (or sum of

TABLE 1(I)

Irrigation uniformity: Barley 1970

Date of I	Nominal amount		Gauged amounts (mm) a	b	c	d	e	Average	Mean
27/5	25·4	SW	34·4	38·7	34·7	30·3	32·3	34·1	31·8
		SE	24·5	33·8	31·8	31·8	25·4	29·5	
2/6	25·4	SW	29·4	31·8	29·4	23·0	25·9	27·9	29·1
		SE	27·5	31·4	34·3	31·3	26·9	30·3	
	Σ 51	SW						62	61
		SE						60	
9/6	25·4	SW	28·4	34·4	29·8	29·4	31·7	30·9	27·0
		SE	22·5	22·5	23·5	24·0	23·0	23·1	
	Σ 76	SW						93	88
		SE						83	
19/6	25·4	SW	28·4	27·8	30·4	28·4	29·4	28·9	27·6
		SE	24·0	25·9	25·9	27·9	27·4	26·2	
	Σ 102	SW						122	115
		SE						109	
26/6	19·1	SW	13·7	17·6	17·6	16·2	15·7	16·2	18·8
		SE	24·9	21·1	20·0	20·0	21·0	21·4	
	121	SW						138	134
		SE						130	
8/7	12·7	SW	9·3	12·7	11·7	13·2	14·6	12·3	10·8
		SE	10·8	8·8	9·8	7·8	9·8	9·4	
	Σ 134	SW	144	163	154	140	150	150	145
		SE	134	144	145	143	134	140	

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two) ends short of the observation to its left it can be assumed that all the water was retained in the profile: when it goes beyond there was probably drainage. On this basis some clear decisions can be reached: Period 5; there was drainage at both I sites; Period 14; there was drainage at the SW site, but not at the SE site; Period 15; there was drainage at both sites. The decision is marginal in Period 8 at the SW site but it must be that all the added water was retained.

The amount of irrigation (Table 1). In ordinary irrigation experiments the intensity is calculated from the total volume of water applied divided by the area it reaches. This is the quantity given under 'Nominal amount', as individual values and as cumulative totals. The 'true' amounts are given as individual catches per gauge round each access tube, as averages for each set of gauges, the mean of these averages, and again, as individual and cumulative values of estimated amounts applied. The scatter and discrepancies are surprisingly small, but one wants the neutron meter to do at least as well, without surprise. Where the meter readings can confidently be interpreted to give an estimate of water gained in the profile as a result of an irrigation operation then the criterion of 'accuracy' is that this estimate should agree with the 'average' amount applied, within the uncertainty associated with the average.

A major test of accuracy (Fig. 6). The basis of the test is a series of diagrams, like Fig. 3 but simpler in structure. The depth axis is now horizontal, and the sign convention is consistent: gains of water are upward, drying is downward. Each point represents the integrated change to the depth at which it is printed, and the points fall into two groups. For the O sites the net drying is plotted for each monitoring position, and the mean line is drawn through them (as on Fig. 3). For the I sites this mean line is used as datum to estimate the relative wetting by irrigation. In irrigation periods a horizontal line is drawn at the 'average' amount (Table 1) (to avoid confusion, standard deviations are not marked).

It is good fortune that the very good agreement between the duplicate O sites (Fig. 3) was maintained throughout the summer. Here the first three pre-irrigation periods are separated, and the main source of the divergence of the I curves between 130 and 150 cm (Fig. 3, left) was in the first period. Otherwise these individual diagrams add nothing to what is in Fig. 3.

It is desirable to look at Periods 6 and 7 first. In both of these the differential wetting, as estimated, comes very close to the average irrigation applied, and, ignoring the possiblity of self-compensating sources of error it can be inferred that the meter was accurate and that the evaporation (plus any drainage) in these two periods was the same for both treatments. If so, it must have been the same in preceding periods, and these can now be examined. In Period 4, the results for the SW hole conform within the acceptable scatter, and so do those for the SE hole, down to 90 cm. During discussion of Fig. 5 it was decided that the meter readings 120 to 150 cm for this hole were unreliable and that in this particular period those for 90 to 120 cm were suspect for the same reason. Rejecting these two readings, Period 4 conforms to expectation.

Period 5 is very different. The second irrigation was applied rather too soon after the first, and there is no doubt that most of it was wasted as drainage (Fig. 5). Assuming equality of evaporation from the two treatments, the gap between irrigation applied, and water gained is a measure of the drainage loss.

Periods 8 and 10 might come into the same category, but all the circumstantial evidence is that in both all of the irrigation water stayed in the profile and the gaps between irrigation applied and water gained are measures of the extra evaporation from the irrigated plots, i.e. the unirrigated plots met a check to transpiration at about the end of

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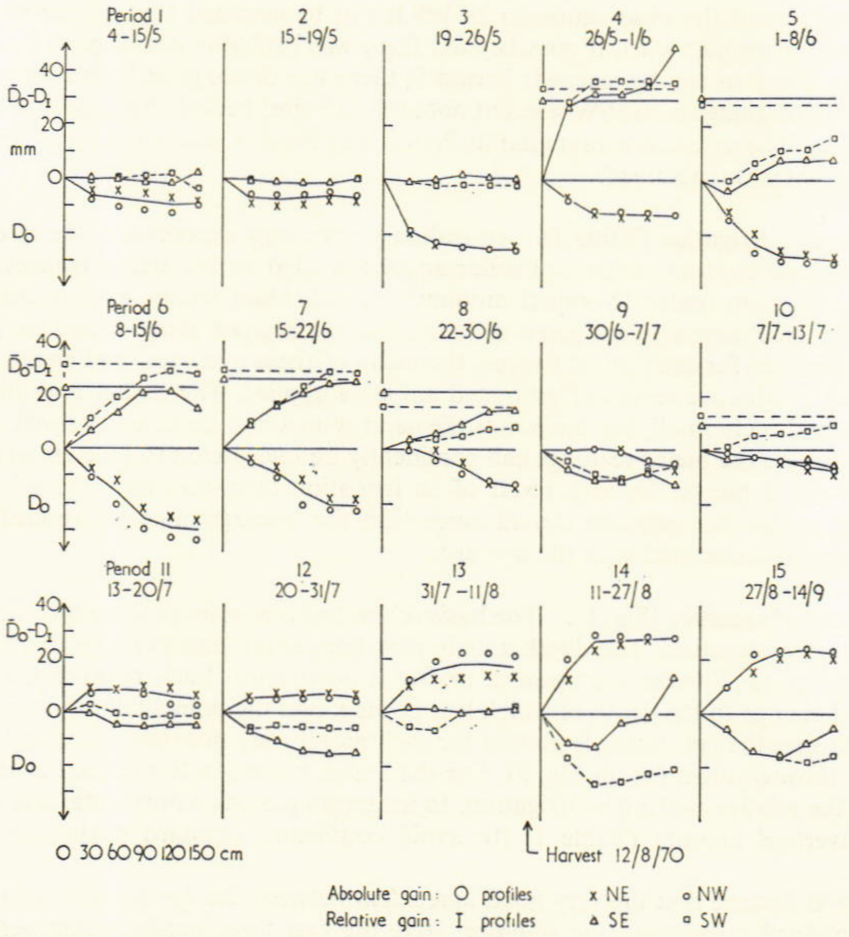

FIG. 6 (I). Accumulated drying, to 150 cm, under barley, 1970. Crosses and circles give D_O, and the line between them is $\bar{D}_O$: squares and triangles give $\bar{D}_O - D_I$. Horizontal lines show measured irrigation, I.

Period 7, coinciding with the beginning of maximum drying in the top 30 cm (Fig. 4) but 20 days after the first detectable differences in the appearance of the two sections of the crop. At this stage the test of accuracy has gone as far as possible: up to the end of Period 7 it is entirely satisfactory, and there will be some support, slight but real, if inferences based on presumed accuracy are confirmed by other evidence from the records.

Doubts about the meter. Up to Period 8 the meter is doing all that could be expected, and from Period 9 onward the readings at the O sites are readily acceptable. But not so those for I sites: here accuracy and interpretation are very much mixed, and for the moment it will be enough to state possibilities, in the hope that after looking at other records it may be possible to weight them as probabilities. First, from Fig. 6, in the Periods 9 to 12, the apparent drying at the SE site is always greater than that at the SW site in the first 30 cm, and in Periods 9 and 11 this is the only difference detectable down to 120 cm. A possibility here is that at site SE plant roots got into the gap between the soil and the access tube, and produced differential drying where the meter response is most sensitive to changes. Hence the few millimetres difference in apparent net drying per period may not be real. There is some support for the continuous near equality of the duplicates in Period 13. By this time all profiles were re-wetting, and in this period the

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sign of the discrepancy was changed, and, in fact, the difference had vanished by 90 cm. This is rather more clearly seen in the detailed diagrams of Fig. 7. The middle one of the set (Period 13) shows the contrast in the way the two profiles were re-wetted. (An aberrant point at 80 cm depth has been interpolated. It is probably the result of a mistake in transcription of the reading on 11 August because there was an (obviously) equal aberration of the opposite sign in Period 14. The question marks show where the unadjusted points would be.) At the SE site the profile was re-wetted to about 30 cm (meter readings changing down to about 50 cm), while at the SW site much of the rain penetrated to about 70 cm (meter readings changing to about 90 cm).

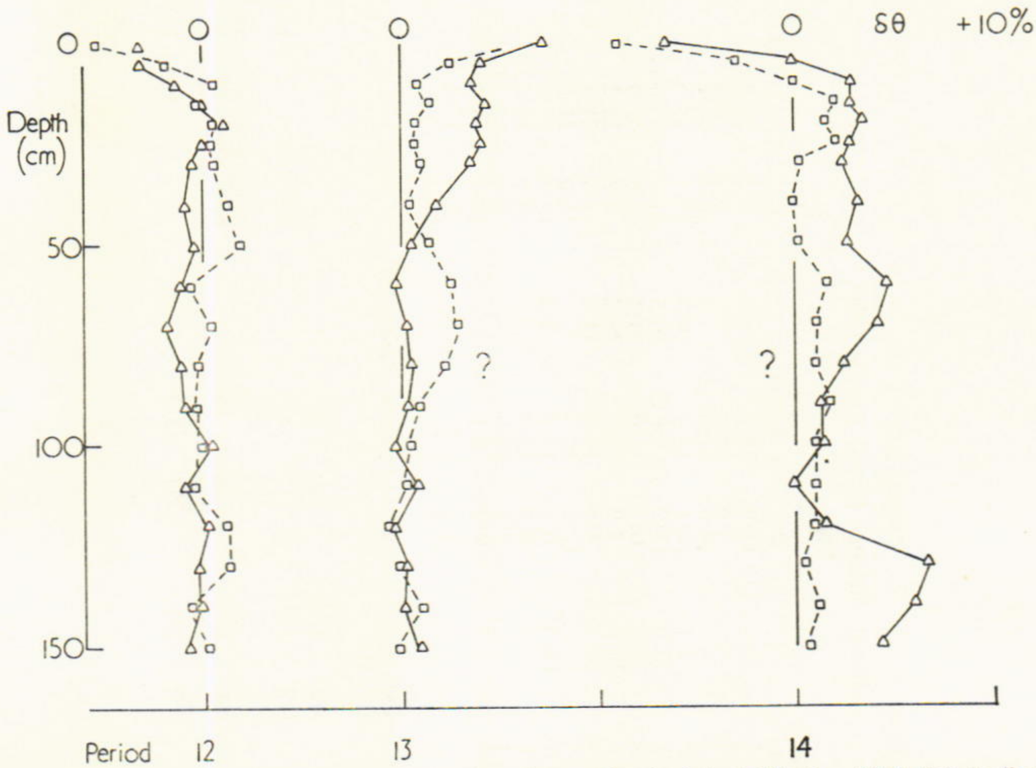

FIG. 7 (I). Profile changes in three periods under previously irrigated barley, 1970, for duplicate treatments.

From study of the detail in the profiles for Periods 9 to 14, it is clear that the SE access tube was flooded near the bottom at the end of Period 9—perhaps had been so for several weeks—and that this water started to drain away during Period 10, and continued to do so during Periods 11 and 12 when the O site profiles were clearly getting wetter (Fig. 6). The process may have come to an end in Period 12, when, as Fig. 7 reveals, the SW profile (squares) shows no important net change below about 60 cm but the SE profile shows drying below 30 cm. Is all of this drainage of perched water trapped immediately outside the access tube? The agreement in the total gains of water in Period 13 (Fig. 6) suggests that all the rain was retained in both profiles, with the difference in distribution already noted, but in Period 14 there is clear evidence of fresh flooding round the SE access tube below 120 cm. Study of similar detail for Period 15 suggested that at the end of Period 14 (Fig. 7) the SW profile was completely saturated below about 20 cm depth and that there was probably some drainage through it in Period 14, but probably none, apart from the leak, below about 100 cm in the SE profile. In terms of

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TABLE 2(I)

Water balance (mm): Barley 1970

	Period	Rain	$\bar{D}_O$	Probable E_O	SW I	SW D	SW $R+I+D$	SE I	SE D	SE $R+I+D$	Probable E_I	Totals E_O	Totals E_I	Totals E_T
1	4–15/5	14·8	8·6	23·4	—	11·9	26·7	—	6·2	21·0	23·8	23	24	25
2	15–19/5	0·0	7·0	7·0	—	6·6	6·6	—	6·8	6·8	6·7	30	30	36
3	19–26/5	2·0	25·6	27·6	—	29·0	31·0	—	26·1	28·1	29·6	58	60	53
4	26/5–1/6	5·3	12·9	18·2	34·1	−24·1	15·3	29·5	−22·1	12·7	14·0	76	74	70
5	1–8/6	0·0	29·8	29·8	27·9	17·2	As for O	30·3	21·8	As for O	29·8	106	104	94
6	8–15/6	1·0	29·8	30·8	30·9	0·1	32·0	23·1	7·8	31·9	32·0	137	136	118
7	15–22/6	1·3	20·8	22·1	28·9	−7·9	22·3	26·2	−4·3	23·2	22·8	159	159	141
8	22–30/6	14·2	13·6	27·8	16·2	4·5	34·9	21·4	−2·3	33·3	34·1	187	193	168
9	30/6–7/7	8·6	6·2	14·8	—	12·1	20·7	—	13·0	21·6	21·2	202	214	187
10	7–13/7	10·4	8·6	19·0	12·3	0·5	23·2	9·4	10·4	29·8?	23·2	220	237	204
11	13–20/7	19·5	−4·4	15·1	—	−4·0	15·5	—	−0·9	19·0?	15·5	236	253	221
12	20–31/7	16·7	−4·8	11·9	—	−0·1	16·6	—	9·4	26·1?	16·6	248	269	244
13	31/7–11/8	25·1	−17·2	7·9	—	−19·0	6·1	—	−18·2	6·9	6·5	255	276	272
14	11–27/8	38·5	−28·0	10·5	—	−4·9	?	—	−26·1	12·4	12·4	266	288	305
15	27/8–14/9	40·1	−22·0	18·1	—	−4·6	?	—	−12·0	?	?	284	?	335

Full season balance—to harvest (Period 13)

		O NW	O NE	I SW	I SE
R		119	119	119	119
I		—	—	150	140
D	0–120	—	—	22	58
	0–150	141	132	28	60
$R+I+D$	0–120	—	—	291	317
	0–150	260	251	297	319

Nominal $I = 134$ mm

Processed $E_O = 255$ mm

Processed $E_I = 276$ mm

$E_T = 272$ mm

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crop behaviour, Periods 14 and 15 are of no importance because harvest was on 12 August, the day after Period 13, and though some of the contrasts and conflicts in Periods 14 and 15 may be effects of the harvesting machinery, these periods are valid testing periods for the performance of the meter. Clearly, quality control is necessary, and no set of unambiguous rules for control can be laid down: there will be occasions (fortunately, not very numerous in the ten years' results to be examined) when readings will have to be rejected as unreliable, without knowing why.

The water balance and probable evaporation (Table 2, Fig. 8)

O sites. The agreement between duplicates is so good that nothing is gained by considering them apart. Table 2 gives, for each period, 0 to 150 cm depth, the value of D_O and of $E_O = R + D_O$, where R is the rainfall of the period. If there was any drainage, E_O will be too big.

I sites. The duplicates are kept separate throughout. For the first three periods the integral is as for the O sites—to 150 cm: thereafter it is to 120 cm only, because of uncertainties in the layer 120 to 150 cm (Fig. 5). In Period 5 the identity $E_I = E_O$ is imposed, for reasons already given. Periods 6 to 9 are straightforward. Periods 10 to 12 raise doubts, expressed in question marks: Fig. 6 suggests, but not very strongly, that there was some anomalous behaviour in the SE profile (roots near the access tube?) and only the SW results are taken into the 'probable' E. In Period 14 only the SE results can be used, and both sets must be discarded for Period 15.

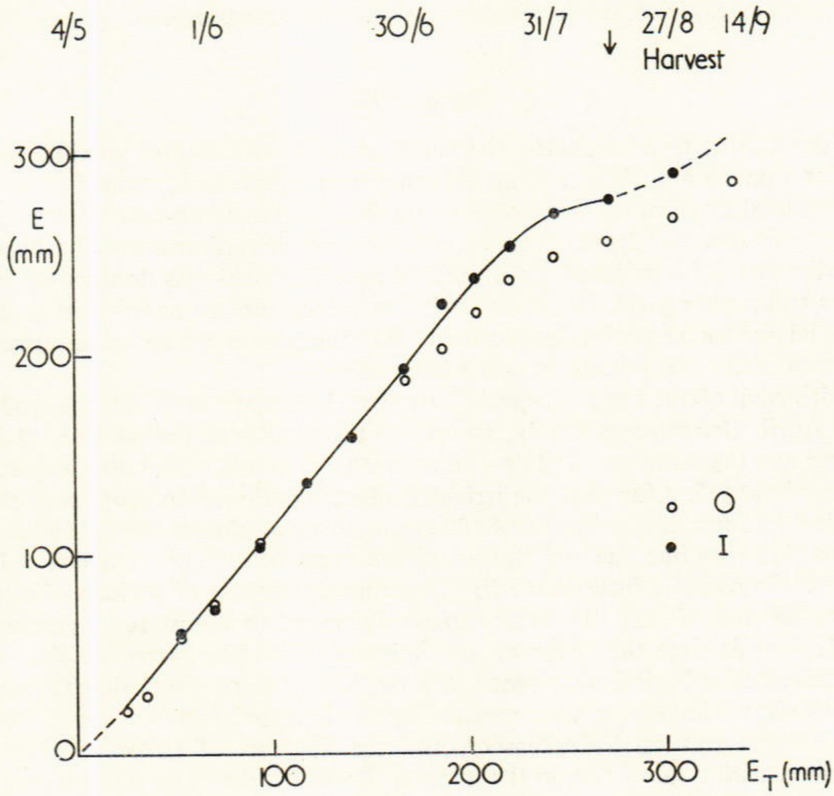

FIG. 8 (I). Evaporation (E) from barley, 1970. Full points are for I sites, open points for O sites. Potential evaporation (E_T) is as calculated for a short grass surface.

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At the foot of the table is a full season balance sheet up to harvest, i.e. ignoring post-harvest Periods 14 and 15. It shows what would have been derived from two sets of measurements only, on 4 May and 11 August, over the depth ranges 0 to 120, and 0 to 150 cm for the I sites, and 0 to 150 cm for the O sites. A few points need comment. First, the duplicate O balances differ by only 9 mm. Second, the effect of truncating the integration at 120 cm, for the I sites, produces differences of only 6 and 2 mm. This can be seen from Fig. 5. Third, the values of $R + I + D$ for I sites exceed the processed value of E_I by 20 and 40 mm (SW and SE). Of this, about 20 mm—for both—is the probable drainage loss in Period 5. The remainder (SE) is the accumulation of differences ignored in Periods 10 to 12. Fourth, the value of $\sum E_I$ is close to $\sum E_T$ for the 13 periods, but this is mainly the result of a decrease in evaporation rate during the ripening phase of the crop. As Fig. 8 shows, over the main growth as a green crop the ratio of E_I/E_T was near 1·15.

It will be an important part of later discussions to look at the relation between the estimated and potential evaporation, seeking explanations for any important differences in terms of meteorology, or plant physiology, or both. In the present context of a proving trial of instrument accuracy, the E_T scale of Fig. 8 is to be regarded as a weighted time scale, on which equal intervals represent equal opportunities for evaporation. For a crop not suffering any check to transpiration, the plot of E against E_T should be a straight line during the main period of active growth. To get a straight line provides a little support for believing the meter to be accurate, but to have failed would have produced no more than a disturbing doubt.

Fig. 8 shows a check to transpiration at O sites at about $E_T \simeq 170$ mm. The deficit, D_O, at this stage was near 135 mm, indicating that the unirrigated barley, in 1970, had produced an efficient deep root system. The final difference in total water use, at harvest, was near 25 mm, about equal to ten days' mid-season transpiration.

Beans, 1970

Though the agronomy is excluded elsewhere, it is of interest and possible importance here. After unavoidably late drilling the crop was never as luxuriant as expected, a condition shared by all other bean crops on the farm and in south-east England generally. Later diagnosis was that the cause was a weevil-borne virus disease and, because water is not a medicament, the irrigated plots suffered too. The yield was doubled by irrigation, but it was still a poor yield. Nevertheless it was a crop, not to be rejected as unsuitable test material for meter performance: such allowances as must be made arise from its being a bean crop—not because it was a poor crop.

It was drilled at about 2 to 3 cm spacing in rows 53 cm apart on 27 March, and emerged about 24 April. Growth was steady, and up to the middle of Period 6 (*c.* 12 June) the appearance was the same on all plots—crop about 50 cm tall, about 50% cover, and leaf area index about 2·5. After that the irrigated plants continued to grow until the end of July (Period 12), reaching a height of 120 cm, a cover of almost 100%, and a leaf area index near 5. Meantime the unirrigated plants grew little. They reached a height of 65 cm, cover decreased a little below 50%, fluctuating because of periods of wilting, and just before the end of July the cover rapidly decreased to about 10%, reached during Period 13. At this time the cover on the irrigated plots had started a slow decrease, greatly accelerated in Period 14, to reach 10% by 28 August, on which date the unirrigated plants were almost leafless, a state reached by the irrigated plants a week later (4 September). Harvest was on 9 September, and the final set of meter readings was on 14 September, with a lot of rain in the interval. Basically, the main interest is in the first 13 periods.

The access tubes were put in place on 27 April, in rows on site Xs, with two in unirri-

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gated plots (O sites, NW and SW), and two in plots that were to receive maximum irrigation (I sites, NE and SE). At each site there were five 'rain-gauges' to monitor irrigation as it was applied, and, as for the barley, the standard deviation was about 10% of the average at each of the seven applications of water. The timings of the irrigation and of the meter readings were always very close to those for the barley, so that for the beans too the first three periods gave four-fold replication of the same treatment.

Profiles, 6 May, and changes 6 to 26 May (Fig. 9). Except possibly in the surface layer, the soil was about as wet as it could be on 6 May. The variety in the shapes of the profiles of water content with depth is as great as that in Figs. 2 and 14, but the range in totals is smaller. On the right of Fig. 9 are the net gains in the three weeks after the first measurements, and the distribution of points is much the same as in Fig. 2, but with a few minor differences. First, below 60 cm (and perhaps not clear in the diagram) the crosses and triangles lie to the right of the circles and squares, i.e. fortuitously, both I sites got a

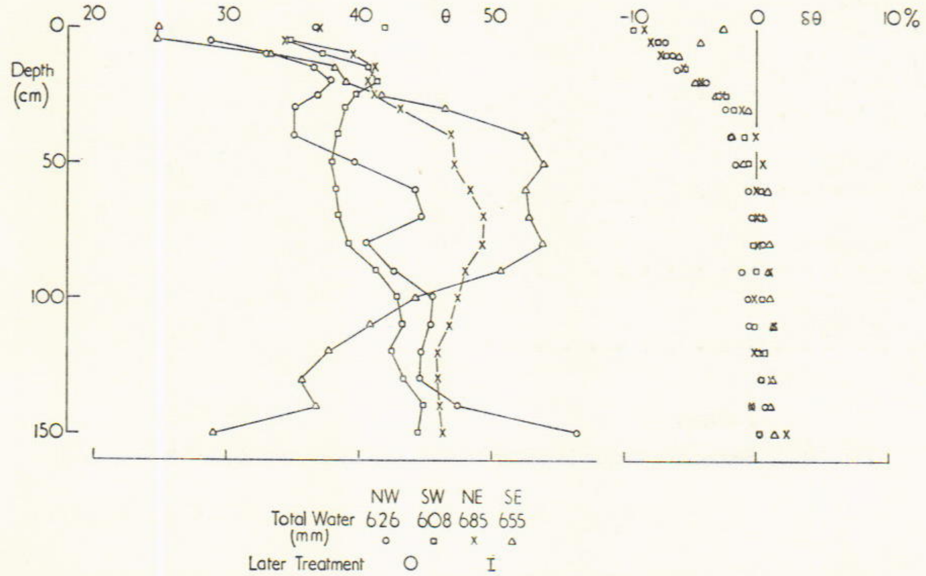

FIG. 9 (I). Water content profiles under beans, 6 May, and changes, 6 to 26 May 1970.

little wetter relative to the O sites. From Fig. 12 this was almost entirely a first period effect, and it is carried through to the evaporation estimates in Fig. 13. Second, at the top, the SE I site seems to have started in a relatively drier state than the other three, possibly because of accidental disturbance of a few centimetres of top soil close to the top of the access tube. Third, for contrast with Fig. 2, below 60 cm depth there is, on average, an indication of a small accumulation of water in the lower part of the soil profile. The total amount is trifling (*c.* 5 mm) but the positive sign suggests that on 6 May the soil profile was very close indeed to 'field capacity': some qualitative reasoning will be based on this presumption, later.

Periodic changes in water content by layers

O sites (*Fig. 10*). As several later diagrams will show, there was rarely any big difference between the periodic net drying at sites NW and SW, so Fig. 10 simply gives the average values. The pattern is much the same as at the barley O sites—a steady value of net drying (*c.* 55 mm) reached in the top 30 cm, another steady value reached later

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between 30 and 60 cm, and similar behaviour 60 to 90 cm. Below 90 cm the small changes may represent slow drainage. As a supplement, Fig. 10 shows the integrated changes in water content, first to 90 cm and then to 150 cm, with the two sites distinguished. The relative positions of the pairs of points changes very little during the season, and the ranges from peak to trough are very nearly the same, so that there would be no serious error in water balance estimates if no more than the 0 to 90 cm observations were used. The evidence suggests that in the study of the water relations of this bean crop all the effects of crop action are confined to a layer less than 90 cm deep.

I sites (Fig. 11). The irrigation kept all except the top 60 cm of the soil profile wet throughout the summer. Except in the top 30 cm the sets of points follow parallel trends,

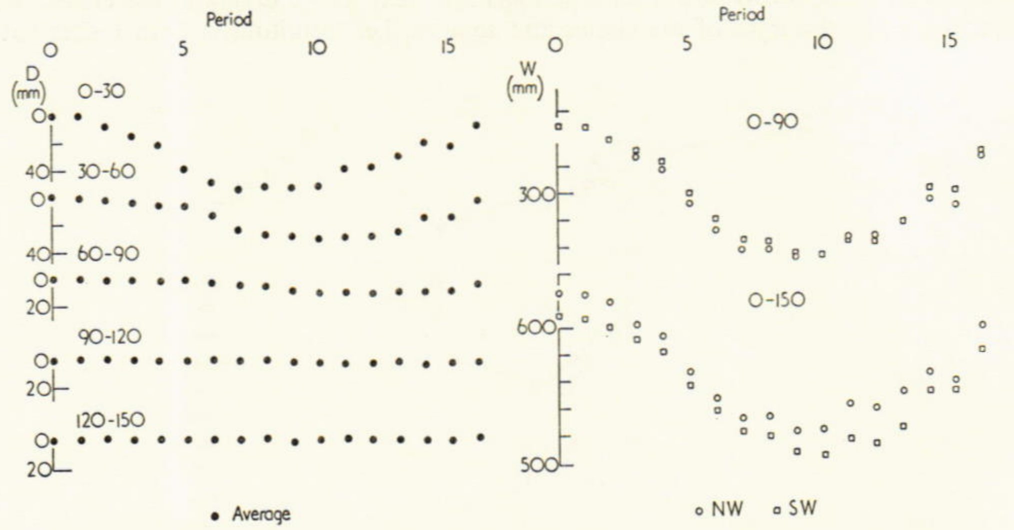

FIG. 10 (I). Seasonal changes in water content, by layers, unirrigated beans, 1970.

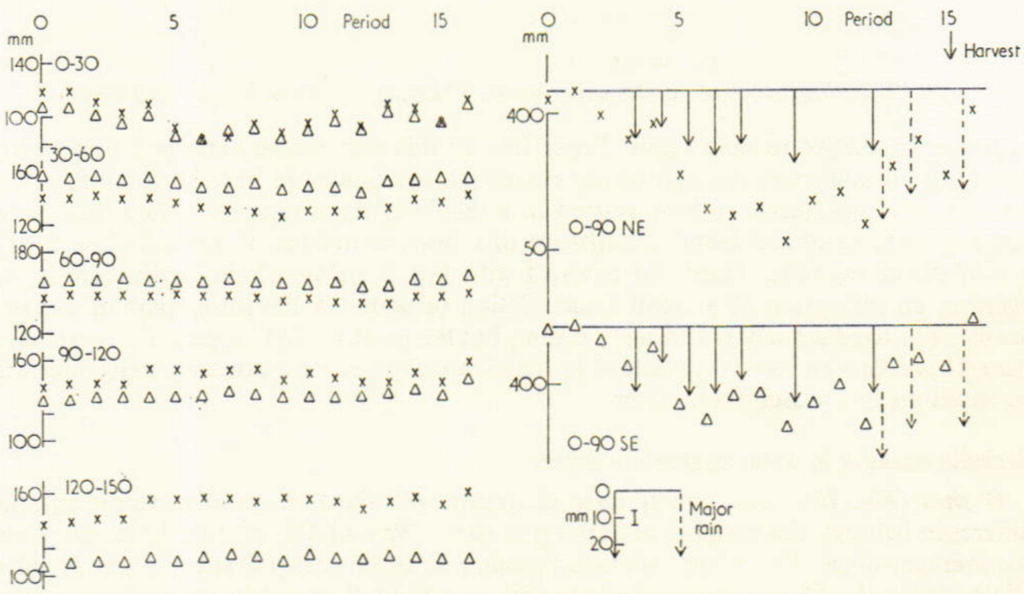

FIG. 11 (I). Seasonal changes in water content, irrigated beans (cf. Fig. 5).

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and in the top layer most of the irregularity is because of differences in amounts of irrigation received. Below 90 cm there is evidence of flooding round the bottom of the NE access tube at the first irrigation, and the effect persisted throughout the summer. If the same thing happened around the bottom of the SE access tube, the effect was slight and short-lived: in an ordinary analysis for a water balance the SE results would have to be accepted because there is no convincing objective reason for rejecting them. However, if the conclusion about the O sites can be carried forward, the water balance for the I sites should be determinable from the changes in water content 0 to 90 cm.

Changes in water content by periods (Fig. 12). The structure of Fig. 12 is the same as that of Fig. 6 with a little simplification. Again, for O sites, the accumulated wetting (upward) or drying (downward) is plotted for the five 30 cm layers, but because the site results often agreed very closely, only their average is given except where they are distinguishable on the scale of the diagram. Results for I sites are separated. As before,

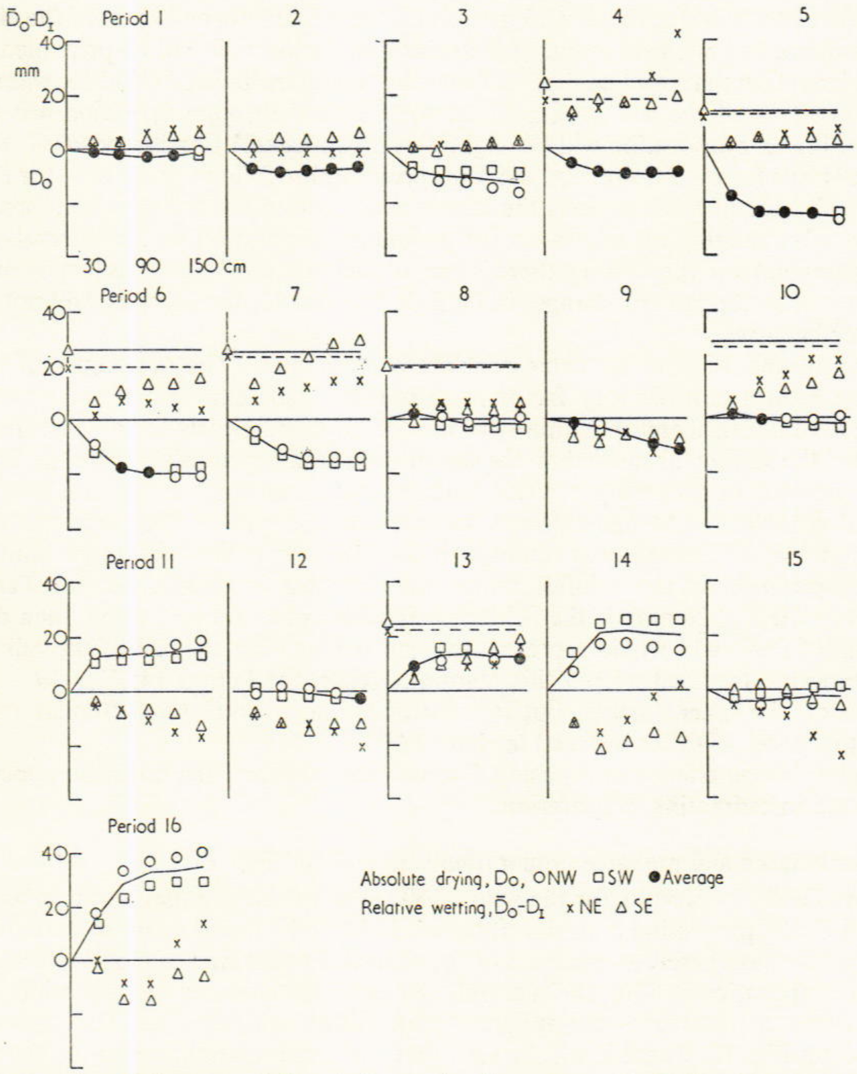

FIG. 12 (I). Absolute drying D_O and $\bar{D}_O$, relative wetting $\bar{D}_O - D_I$, and irrigation, beans 1970 (cf. Fig. 6).

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the points represent the relative gain in water at I sites with respect to the average O site change as datum.

Fig. 12 cannot be used in the same way as Fig. 6 because there is no period after the third in which it is possible to state with confidence that the evaporation from O and I plots was the same and that there was no drainage from I plots. As already noted, there was a small relative gain of water in the I profiles during the first period, but there was no significant difference in the second period, and none at all in the third period.

In the water balance, to follow, the whole range, 0 to 150 cm, will be used for the O sites, i.e. working to the end of the lines drawn through O points on Fig. 12. For I sites only the range 0 to 90 cm will be used, and selectively between the two sites, for reasons based on Fig. 11. Results for the two sites are separate, for clarity, and on each part is a horizontal line through the maximum water content measured, thought to be an adequate approximation to field capacity at the beginning of the season. As before, the vertical arrows represent the amount of irrigation applied, usually, but not always, on the day after the preceding set of moisture meter readings. For three periods, major rain is represented by broken arrows, one of them (Period 13) coming after an irrigation.

It will be noted that for the first 13 periods all the NE arrows end short of the cross that precedes them, so that, with a marginal decision in Period 5, it will be presumed that all rain and irrigation that reached the NE I sites, up to and including Period 13, was retained in the top 90 cm of the soil profile. (That some leaked through in Period 4 is obvious from Fig. 11, i.e. evaporation will be slightly over-estimated.) For Periods 6, 7, 8 and 10 the same is true for the SE site, and the same presumption follows. But not so for Periods 4 and 5, or for 13. In these periods the arrow ends beyond the triangle that precedes it, and even after making an allowance for probable evaporation in the interval between the measurement and the wetting, there is very little doubt that water was lost by drainage. The values of water content changes in Periods 4, 5 and 13, for SE sites, will not be used in a water balance.

Periods 14 and 16 have the same problem at both sites. (The senescence of the crop may have been a contributory factor in setting the problem, but is not a reason for ignoring it.) In both there were almost 40 mm of rain, and clearly for at least the SE site this wetted the soil by far more than the deficit measured previously. Again the SE results must be ignored in preparing a water balance, but those for the NE site need not be jettisoned completely. At one extreme, assume that, in spite of the diagram's evidence to the contrary, all the rain was retained in the NE profile: then an upper limit to estimated evaporation is the rainfall minus the decrease in deficit, i.e. for Period 14, $E < 38{\cdot}6 - 10{\cdot}5 < 28$ mm. If the field capacity concept could be trusted, then the cross at the end of Period 14 would represent the new drying after the end of the rain period, i.e. the evaporation must exceed this amount. Hence, for Period 14, $E > 19$ mm. (The argument can be taken further, but it is tortuous and inconclusive.) Similar reasoning applied to Period 16 (after harvest) leads to $14{\cdot}0 > E > 8$ mm.

To maintain consistency in occasional somewhat arbitrary decisions the upper values will be used in estimating evaporation.

The water balance and probable evaporation (Table 3 and Fig. 13)

O sites, Table 3. Results for the whole 150 cm of profile are used, and up to the end of Period 10 the processing is straightforward. In Period 11, and again in Periods 14 and 16 there is selection based on rejection of the absurd. For the first of these, at site NW the apparent evaporation is 19·6–18·7 i.e. only 0·9 mm. At the same site in Period 16 there was even greater absurdity—the apparent evaporation was negative! The choices made are based on Fig. 12, where it will be seen that the accumulation curves for the SW site much more nearly approach a constant value than those for the NW site, particularly in

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TABLE 3(I)

Water balance (mm): Beans, 1970

	Period	Rain	D_O NW	D_O SW	Probable E_O	NE I	NE D	NE $R+I+D$	SE I	SE D	SE $R+I+D$	Probable E_I	Totals E_O	Totals E_I	Totals E_T
1	6–15/5	14·8	0·5	2·1	16·1	—	−3·3	11·5	—	−1·6	13·2	12·4	16	12	19
2	15–21/5	0·5	6·6	7·1	7·4	—	9·3	9·8	—	5·0	5·5	7·6	24	20	35
3	21–26/5	1·5	16·3	9·2	14·2	—	9·7	11·2	—	9·9	11·4	11·3	38	31	48
4	26/5–1/6	5·3	9·2	8·9	14·4	17·8	−7·1	16·0	24·5	?	As for NE	16·0	52	47	70
5	1–8/6	0·0	26·3	24·7	25·5	12·6	19·3	31·9	13·7	?	As for NE	31·9	78	79	94
6	8–15/6	1·0	20·4	17·7	20·0	19·5	12·9	33·4	25·4	5·9	32·3	32·8	98	112	118
7	15–22/6	1·3	14·2	16·8	16·8	23·5	2·6	27·4	25·7	−8·5	18·5	23·0	114	135	141
8	22–30/6	14·2	−1·0	3·7	15·6	19·3	−3·8	29·7	19·8	−1·5	32·5	31·1	130	166	169
9	30/6–7/7	8·6	11·2	11·5	20·0	—	12·4	21·0	—	13·1	21·7	21·4	150	188	187
10	7–13/7	10·4	−1·1	3·7	11·7	26·6	−14·8	22·2	28·1	−9·0	29·5	25·9	162	213	204
11	13–20/7	19·6	−18·7??	−13·6	6·0	—	−3·3	16·3	—	−6·7	11·9	14·1	168	228	221
12	20–31/7	16·8	2·6	3·7	20·0	—	12·8	29·6	—	15·2	32·0	30·8	188	258	244
13	31/7–11/8	25·1	−11·6	−11·8	13·4	22·0	−21·4	25·7	24·4	−23·7	25·8	25·8	201	284	272
14	11–27/8	38·6	−13·9??	−26·0	12·6	—	−10·3	<28·3	—	?	As for NE	28·3	214	312	305
15	27/8–7/9	2·0	6·6	−0·5	5·0	—	13·6	15·6	—	?	As for NE	15·6	219	328	327
16	7–14/9	37·9	−40·6??	−29·2	8·7	—	−23·9	<14·0	—	?	As for NE	14·0	227	342	336

Full season balance

		O NW	O SW	I NE	I SE
R		198	198	198	198
I		—	—	141±10	162±7
D	0–90 cm	24	21	5	−2
	0–150 cm	27	28	−33	−20
$R+I+D$	0–90 cm	222	219	344	358
	0–150 cm	225	226	306	340

Nominal $I = 159$ mm

Processed $E_O = 227$ mm
Processed $E_I = 342$ mm
$E_T = 336$ mm

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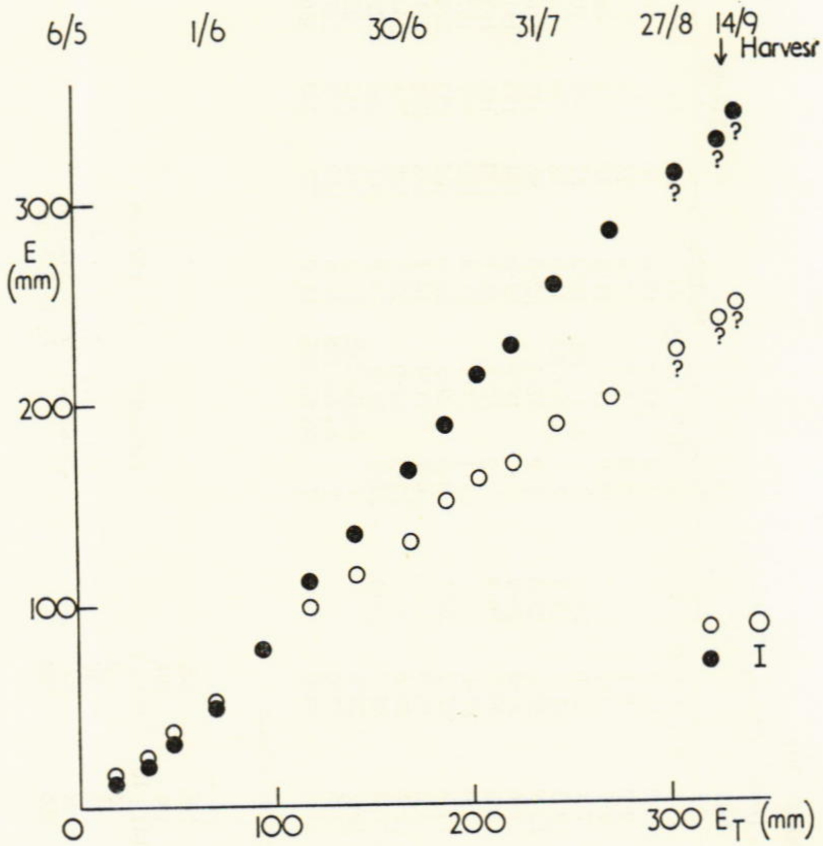

FIG. 13 (I). Evaporation, beans 1970 (cf. Fig. 8).

Periods 14 and 16. The quantitative effects of the choices are in the full season water balance at the bottom of the table, and, taking everything in—absurd or not—the NW and SW balances agree very well both over the full profile depth and for a limited 0 to 90 cm soil depth: as noted earlier, the 0 to 90 cm depth would have been adequate. The effect of the selection imposed is to increase the total estimated evaporation by a millimetre or so, and it is the selected values that are plotted as accumulated total on Fig. 13.

I sites, Table 3. For reasons already given, five results for site SE are ignored: otherwise all values of probable average evaporation are averages for the two sites.

Again in the lower part of the table the full season water balance is given, for two depths, as it would be obtained from readings on 6 May and 14 September. The NE value of E, 0 to 150 cm, is not reliable because of the behaviour of the meter, and the SE value of E, 0 to 90 cm, is an over-estimate, because of drainage.

The estimated potential evaporation for the whole period is very close to the probable value of actual evaporation, a chance result because the actual evaporation was relatively smaller while the crop was small and establishing a leaf cover, and again during the period of senescence when leaves were dying and falling. In the periods of adequate cover, the ratio E/E_T is about 1·15, the same as for barley.

It must be accepted that the meter can produce absurd results. Some will occur when there is flooding of the space around the bottom of the access tube, and where, as in Fig. 11 for the NE site, the effect is easily recognised then results can be rejected. Others may occur because of differential wetting without flooding, and it is possible that the

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confused results in Periods 14 and 16 at the O sites (Table 3) were produced by very irregular rainfall penetration caused by dripping from wet haulms or weeds (14) or by the stubble and trash left after harvest (16). In time these effects will tend to average out, and it might be noted that the sums of the two major regains (Periods 14 and 16) are near 55 mm for both NW and SW sites and it is because of this that the full season balances in Table 3 agree so well.

In contrast with the barley, the unirrigated beans suffered a check to transpiration early in the season (at about $E_T = 90$, Fig. 13) when the deficit, D_O, was near 50 mm. The difference in total water use increased throughout the season, and at the last reliable set of measurements before harvest it was near 90 mm, about one-third of the value of E_I at the time.

Sugar beet, 1970

Though a barley crop may be acceptably uniform, and a bean crop almost so, a sugar beet crop can never be regarded as uniform in the soil however uniform the leaf cover may become. Apart from the spacing problem, as the root itself gets bigger it fixes an increasing volume of effectively static water that may perturb horizontal averages within range of the meter. With rows at about 50 cm apart the meter cannot respond to anything happening in any row other than the one it is in, nor even to changes in water content mid-way between rows. The patterns of root distribution and of rain shedding by the leaves may have important effects on what the meter responds to. Within the rows there is a similar problem. The spacing after singling was from 15 to 25 cm and the access tubes were set about midway between two plants at about average spacing. Only these two plants could have any effect on meter readings, and this must be remembered throughout all that follows. There will be occasions to leave a puzzling result unexplained, or to reject it as absurd: with two plants employed to represent the behaviour of thousands, these occasions are remarkably few, and provide no basis for any indictment of the accuracy of the meter.

The crop was drilled on 24 April at 53 cm row spacing, emerged about 5 May, and was singled to about 20 cm plant spacing on 28–31 May. The sites were Mn and Ms,

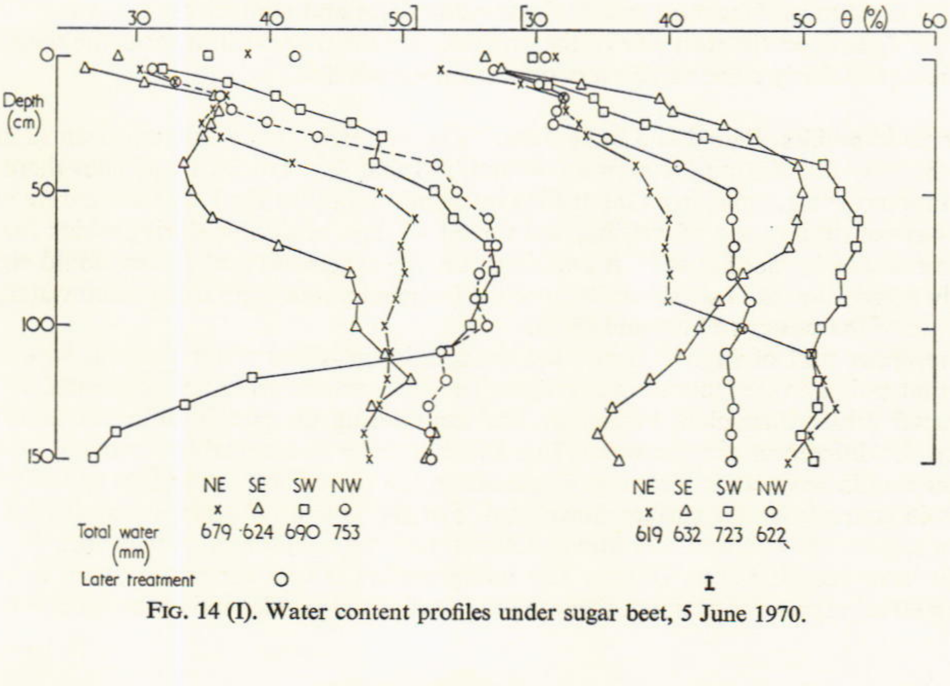

FIG. 14 (I). Water content profiles under sugar beet, 5 June 1970.

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and access tubes were inserted on 2, 3 and 4 June at about 25 m in from the edges, four per plot at about 40 m apart parallel to the sides (Fig. 1). The first profiles of water content were measured on 5 June, four days after the fifth measurement on the barley plots, with no rain in the interval. The crop responded to irrigation as it usually does: by the time of the second application there was a detectable difference in the sizes of the plants, and a week later the plant cover at I sites was twice that at O sites. The ratio was maintained until mid-July (end of Period 6) when the cover at I sites was complete. Thereafter the O plants rapidly completed their cover. This brief statement about the course of development is important here because it means that only in the very first of the early periods could the two sites be regarded as meteorologically equivalent in terms of plant cover.

There was irrigation in the first period, but too much was applied, and the sugar-beet experiment cannot be used to provide the kind of internal calibration of the meter that was provided by the barley. So the treatment set out in Fig. 6 cannot be employed here.

Profiles, 5 June 1970. Fig. 14 repeats the variance noted in Figs. 2 and 9, with a noteworthy extreme for the SW O site between 100 and 150 cm depth. This shows the effect of a layer of sand, and because of the shape of the meter response curve (L. & F., Fig. 5) the transition was quite abrupt: any tilting in the interface would add to the gradual appearance of the measured change. The interface is near 120 cm, and it is to be expected that the drainage characteristics of this SW O profile will differ from that of the others (see Fig. 15).

As a minor point, note the water content at 130 cm, site SE O. This, if real, represents a drier layer, more severely drier than shown because of the smoothing effect in the meter response. It could be the effect of displacing a flint in the process of drilling the hole for the access tube, producing an air cavity that might persist to give distorted 'dry' readings when empty and distorted 'wet' readings if it filled with water. It might collapse under the over-burden, and the anomaly would disappear, slowly, or quickly.

Allowing for a few millimetres of net drying between 28 May and 5 June the range of water contents, near the maximum possible, is from about 630 to 760 mm in the 150 cm of profile—about the same as under the barley and bean sites. Within the groups on Fig. 14 the two profiles most nearly the same in form and content are those for NW O and SW I, both on the west side of the experimental area, i.e. well towards the middle of the field, and fairly close neighbours on a north–south line.

Changes in profiles, Period 1, 5 to 16 June. The first irrigation was applied on 12 June, and the only rain during the period (1·0 mm) fell that day. So, for the O sites there was continuous drying, apart from the trifling interuption, but for the I sites there were seven (−) days of drying, one of wetting, and three (+) days of drying, during which the soil surface would be wet for at least two days, i.e. the evaporation at I sites would significantly exceed that at O sites, not because the irrigated plants were using more water, but because of the wetter soil around them.

The upper part of Fig. 15 shows the changes in measured water content, with three aberrant points to be ignored in averages. The changes are probably dominated by soil character rather than plant behaviour, and considering the greatly different data from which the differences are measured (Fig. 14) the scatter is acceptably small and average values should have some meaning. These are in the right hand upper part as integrated gains in water from the surface downward. For the O sites, the net drying is 15·8 mm down to about 60 cm, and 14·2 mm to 150 cm; had the monitoring gone deeper the total might have been less than 14 mm. The interpretation is that the relative gain in water below 60 cm represents drainage from the top part of the profile, and in the water balance

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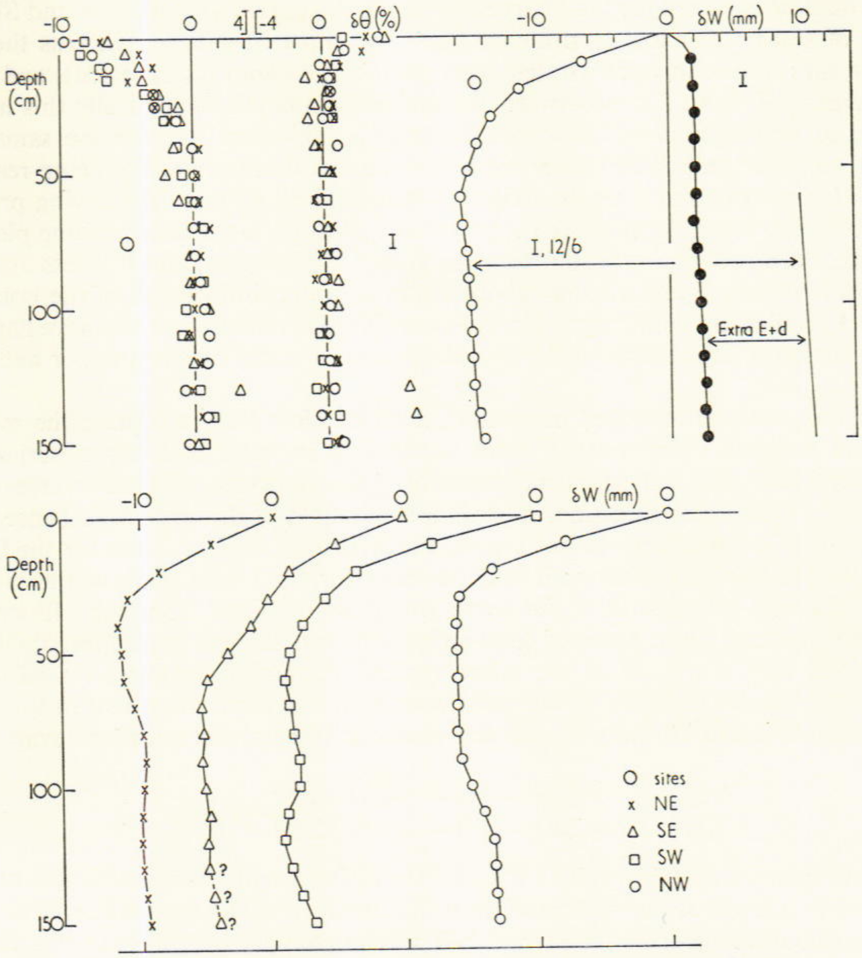

FIG. 15 (I). Top, left. Changes in water content, sugar beet 5 to 16 June, with Ī = 25 mm on 12 June. Top, right. Average accumulated change with depth: O sites drying to left, I sites wetting to right. Full line is 25 mm to right of lower O site points. Bottom. Individual accumulated changes with depth at O sites.

for the period the evaporation is $E_O < 14 + 1{\cdot}0$ ($R = 1{\cdot}0$ mm), but will be taken as $E_O \equiv 15$ mm, accepting the near certainty that it is a slight over-estimate. (The coarser treatment used to produce Table 4 gives $E_O = 13 + 1$ mm, because it includes the SE value at 130 cm.) At the I sites all the important change took place in the top 10 cm of the profile, and this is a somewhat fantastic result after a sequence of drying, wetting, drying, that all the rest of the (average) profile should get back to where it started from. As this is a probing exercise to see what the meter does, it will be helpful to examine the individual profiles at O sites. These are in the lower part of Fig. 15, with the end of the SE profile queried because of the anomalous reading at 130 cm: a smoothed value was interpolated. The shapes differ somewhat, but not greatly from the average O curve above them, with an interesting variant for the SW curve (squares). Here, from 60 to 100 cm, there is evidence of water accumulating by downward drainage from above, then of relative drying in the next 20 cm, and finally of further accumulation to 150 cm (and beyond). This is probably an effect of the sand layer, itself draining at the top, and, when drained, acting as a barrier to drainage from the clay above it. The maximum drying on these four curves has values near 12, 15, 19 and 16 mm, and a similar sort of spread would be expected for the I curves. Of these, the curves for sites NW and SE show evidence of some water lost as drainage (they had most irrigation), whereas the other pair show an increase in water content over part of the depth (as expected), and then a small decrease of about 1 mm between 100 and 150 cm depth. Statistically this must be dismissed as non-significant, but qualitatively it is important because the same thing happened in other years when there seemed to be less doubt about its being real. It is unlikely to have occurred after the irrigation was applied, so this deep drying probably took place in the seven days before the irrigation. With no more than seedling plants on the surface, deep root action would seem an absurd explanation, and it is less absurd to suggest that between 5 and 12 June about 1 mm of water drained out of the bottom of these two I profiles. If this is acceptable as a plausible explanation, it could have happened at the O sites too, *in addition* to the re-distribution of water between upper and lower layers.

Out of this, without extended discussion, it seems clear that, accepting the meter as precise and accurate, there must be some uncertainty in water balances in periods that begin or end with the soil near field capacity, As it happens, all these sources of uncertainty act in the same direction, as an under-estimate of drainage and, hence, as an over-estimate of evaporation. In this period, the error may be 1 or 2 mm for the O sites, perhaps 10% of the evaporation: it may be more for the I sites, and, at the moment, probably the best estimate of E for these would be obtained from the NE and SW results only, because these received least irrigation, and there is some probability that they retained very nearly all of the water applied. Assuming complete retention, and that the net retention is given by the maximum gain measured anywhere in the profile (NE; 3·9 mm at about 50 cm: SW; 2·9 mm at about 100 cm) the estimated evaporation is

$$\left.\begin{array}{ll} \text{NE} & E_I = 22{\cdot}6 + 1{\cdot}0 - 3{\cdot}9 = 19{\cdot}7 \\ \text{SW} & E_I = 24{\cdot}7 + 1{\cdot}0 - 2{\cdot}9 = 22{\cdot}8 \end{array}\right\} 21\ \text{mm}$$

The average value of E_O (above) is 15 mm and the difference of 6 mm is about what might be expected as a result of the wetting of the soil at the I sites. The gap on Fig. 15 is 8 mm, suggesting that drainage from the SE and NW sites might have been about 4 mm through each.

Seasonal changes by layers (Fig. 16). At both O and I sites the four sets of measurements lie in fairly narrow bands, with occasional changes of relative position that may represent root activity close to an access tube. Below 30 cm the band width is variable, as would be expected from the profiles on 5 June (Fig. 14). At 60 to 90, and 90 to 120 cm at the NW O site there is clear evidence of more rapid extraction of water than at the SW site (real effect? or roots near the access tube?). At 120 to 150 cm, SW site, there is little change throughout the season.

The changes 0 to 30 cm at I sites are affected to some extent by differences in the amount of irrigation they got, but at 30 to 60 and 60 to 90 cm the patterns are almost identical with very little change in water content throughout the season. At 90 to 120, and 120 to 150 cm the same is almost true for three of the sites with evidence of net drying in the 90 to 120 cm layer. Is this root action? or drainage? The results at the fourth site (SE) are useless for the first seven periods, 90 to 150 cm. Again, the cause is thought to be flooding of the gap between tube and soil at the bottom of the access hole.

Changes with depth (Fig. 17). The technique used on the barley records (Fig. 6) cannot be used here because the irrigation quickly produced a difference in plant cover at O and I sites. So a simpler variant was tried on all 16 periods, but is here displayed for only

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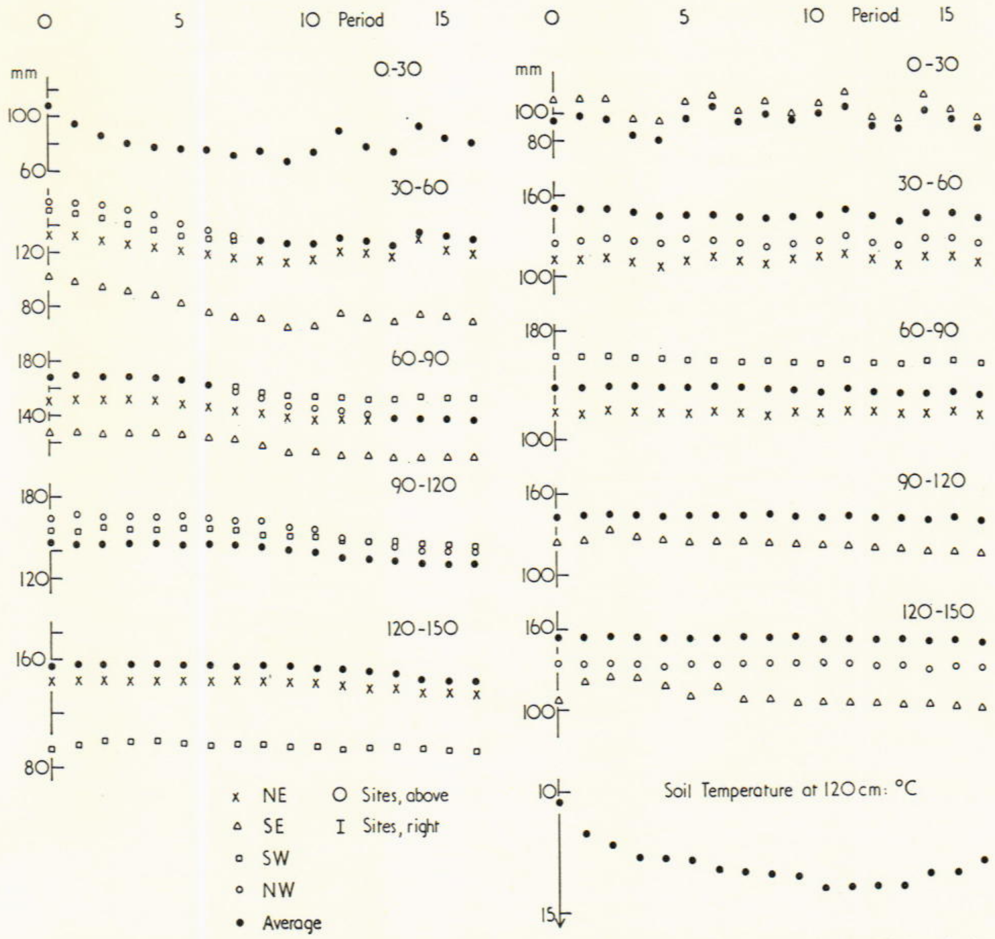

FIG. 16 (I). Seasonal changes in water content by layers. Left: unirrigated sugar beet. Right: irrigated sugar beet 1970.

four, because seven raised no problems, and the other five raised only marginal difficulties resolvable in other ways. As part of the testing of the meter, results for Periods 9, 10, 14 and 15 are looked at in some detail. The curves on the left hand side of Fig. 17 are plotted as accumulated wetting (upward) by 30 cm layers down to 150 cm, and as there was irrigation in Period 9, the measured irrigation is included for I sites to make I and O results homogeneous. All curves start from zeros spaced at 10 mm intervals, and the order of plotting is chosen to emphasise contrasts. In an ideal system of absolute uniformity all curves would be parallel and, if no water has been lost from the profile, should reach limiting values before 150 cm—at 10 mm intervals: the I site group for Period 10 shows something of the sort, and three of the O site group are not seriously discordant, either among themselves or with the I site results.

It is more convenient to consider Periods 14 and 15 first.

Period 14 was very wet (rain = 37 mm) and all eight profiles show gains of water. The I site curves are in fair agreement showing, on average, about 20 mm net gain in the period, to give $E_I \simeq 17$ mm. Expectation is that the values of E_O should be about the same, and though this is true for SE and SW sites (triangles and squares) it is absurdly wrong for NE and NW sites. At the NE site, the maximum gain is 34 mm (at 60 cm depth): at the NW site the maximum gain is 37 mm (at 90 cm depth). Dashed lines on the

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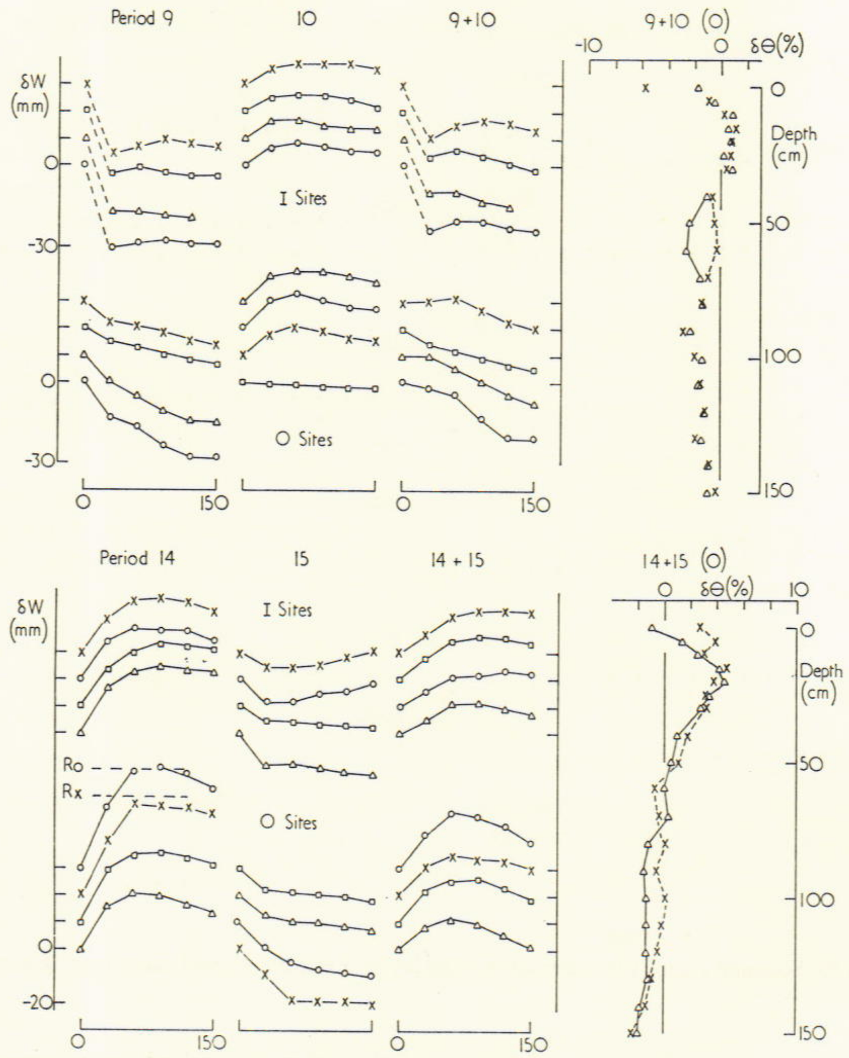

FIG. 17 (I). Sugar beet 1970. Left. Accumulated wetting and drying to 150 cm for problem periods, singly and combined. Right. Profile changes, NE (X) and SE (Δ): O sites, top right, 30 July to 12 August, and bottom right, 10 to 28 September 1970.

diagram show the amount of rainfall, from the appropriate zero for each of the two sites. In Period 15—net drying—the curves clearly fall into characteristic pairs that are the same as the obvious pairings in Period 14, namely NE and NW (crosses and circles), and SE and SW (triangles and squares), at both I and O sites.

As for all periods, the values plotted are differences between the beginning and the end, and an error at the end of Period 14 would affect both Period 14 and Period 15 by equal and opposite amounts. There are two obvious courses of action here, the first being to combine the two, as in the third diagram of Fig. 17. The result is that seven of the curves are acceptably concordant, the aberrant one being for the SE O site (triangles). Leaving this for special consideration, the inference is that something went wrong on the occasion of the 14/15 measurements. Reference back to the field records shows that on this occasion there were somewhat unusual conditions, but they were *not* expected to be detectable in this kind of behaviour. Briefly: the measurements at the end of Period 14 were started on 21 September, but were interrupted by rain at a time when four profiles

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had been done, namely SE and SW at I sites, NE and NW at O sites. The measurements were completed next day, using meters newly switched on. There has never been any suspicion previously that an extended 'warming up' time was needed for accurate measurements, and it may be completely irrelevant to the fact that the pairs notable in Periods 14 and 15 coincide with the distribution of the measurements between the two days. If one of these sets is to be labelled as 'wrong' it is that of the first day, including as it does the absurd apparent gains at the NE and NW O sites, and the doubtfully large gains at the SE and SW I sites. Guessing, it may be that the drizzle of 21 September affected the meter's behaviour, or even wetted the outside of the probe.

All the Period 9/10 measurements were made on the same day, and the doubt is confined to the O sites. Combining the two periods produces some improvement, suggesting that on the day of the 9/10 readings they may have been over-estimated in the first 30 cm of each of the profiles of NE and SW sites. But even so, the NE site readings are still apparently out of step with the other three. Comparing the combined Periods 9 and 10, with 14 and 15, the SE site seems normal in the first but not in the second, whereas the NE site seems normal in the second but not in the first. Figure 17 shows the changes in soil water content for the two double periods for each of these sites. It reveals where the differences occurred, but little more. In the upper part of the diagram (9 and 10) the difference occurs in two readings only (the agreement elsewhere is extraordinary), and this could be produced by a localised anomaly at about 55 cm—possibly the flooding of a hole produced by a displaced flint at the NE O site in Period 10. The corresponding profile changes in Periods 14 and 15 (lower right, Fig. 17) remain as a puzzle. The two chosen reproduce what would have come out of all four sets of measurements at O sites—wetting down to about 60 or 70 cm, and drying below, with no hint of a limit being

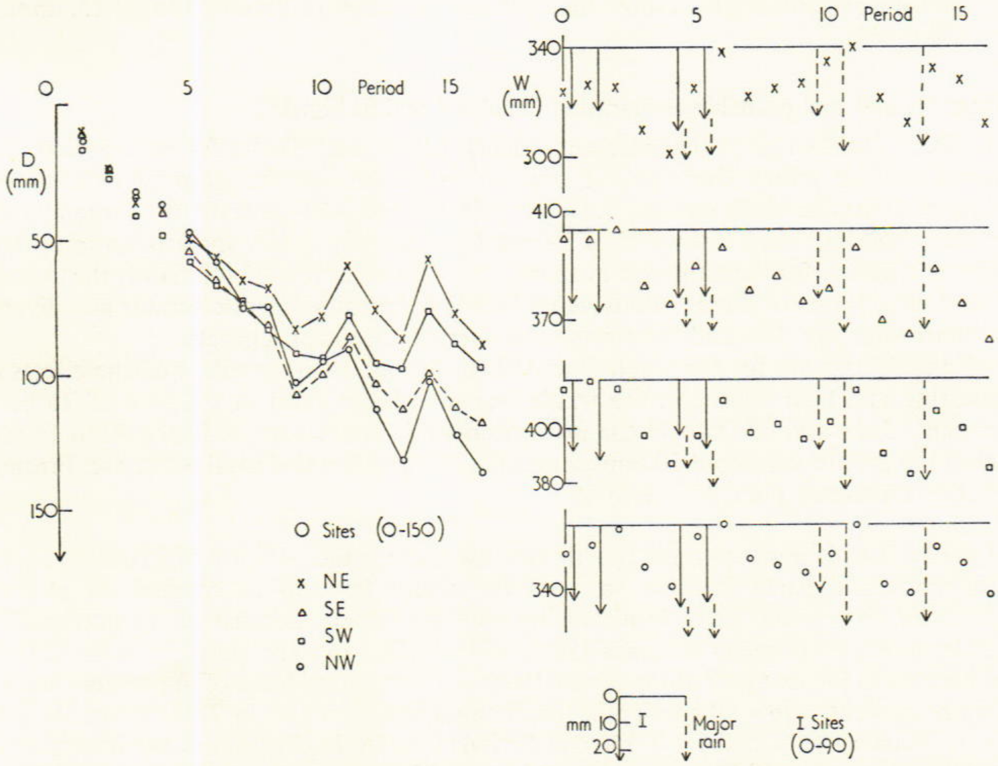

FIG. 18 (I). Drying, sugar beet 1970. For O sites *changes* start from zero on 5 June. For I sites the values are *absolute* water contents, 0 to 90 cm. Amounts of irrigation and major rain are shown.

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reached, or even approached, at 150 cm. Most of this occurred in Period 14, and neither of the obvious possible explanations is readily acceptable. They are: (i) vigorous, very deep root activity in a period of excessive rain; (ii) drainage that occurred before the rain started.

Seasonal changes in deficit (Fig. 18). The left-hand side shows the net drying at O sites, down to 150 cm, from a zero on 5 June 1970 (for I sites the spread is less, even with differences in irrigation amounts). There is a small divergence up to about Period 7, and thereafter it increases rapidly until, at the last reading, the range is only a little less than half of the average. For I sites, Fig. 18 suggests that there was not a lot of change in water content below 90 cm depth, and the right-hand side of Fig. 18 shows the changes to this depth, with a horizontal line through the wettest measurement of the season: it may be at least 10 mm too low. As before, amounts of irrigation, and of major rain, are shown by arrows, and the criterion for possible drainage is that the end of a downward arrow—or the sum of two—must be far beyond the measurement point to its left. Ignoring periods in which there is no problem, a few remain for comment:

Period 1. Sites SE and SW almost certainly qualify as 'drainage' sites, and probably NW too.

Period 2. These three sites all qualify, again.

Periods 5 and 6. Looking at the two periods together, sites SE and NW probably had drainage, while NE and SW sites may have had none, at least in one period.

Period 11. There is strong presumption of drainage at all four sites, least strong at SE and SW sites.

Period 14. There can be no presumption of drainage on the evidence of the diagram, and it does nothing to resolve the confused situation in Periods 14 and 15, already discussed.

Water balance and probable evaporation (Tables 4 and 5, Fig. 19)

O sites. Table 4 gives the increase in deficit (D) at each O site for each period, and pairs of average values. One pair, NE and SW, is for the sites that gave the two smallest values of D for the whole season; the other pair, SE and NW, gave the two largest values for the whole season. To the end of Period 6, as already noted, there is no important difference, and so for the estimated evaporation, as an accumulated total, only the average of the four is given for these periods. After Period 6 the pairs differ detectably and diverge (compare with Fig. 16), and the two sets of averages are kept separate.

All the deficits are for the whole 0 to 150 cm of monitored profile, and the effects of truncating at 90 cm appear in the whole season balance sheet at the foot of Table 5. Between 5 June and 12 October the extra decrease in water content in the 90 to 150 cm part of the profile was about 30 mm, some 10% of the estimated total water use. Presumably this represents plant root activity.

I sites. This is more complex, partly because there is the addition of irrigation to the parameters, and partly because some of the results have to be rejected, or at least questioned, for reasons given in discussing previous figures. Because of the unreliability of at least one set of meter readings 120 to 150 cm (Fig. 16), and possibly 90 to 120 cm, and because in the first part of the season there is not much evidence of important changes of water content below 90 cm depth, the changes in deficit (D) in Table 4 are for 0 to 90 cm, Periods 1 to 8, and for 0–150 cm, Periods 9 to 16. In the light of the immediately preceding discussion of Fig. 18, supported by earlier statements of doubt, the values of $R + I + D$ are in three groups (up to Period 13). Those figures unqualified are accepted

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TABLE 4(I)

Water balance (mm): Sugar beet, 1970

Period	Rain	*Do* NE	*Do* SE	*Do* SW	*Do* NW	Probable *Eo* NE, SW	Probable *Eo* SE, NW	NE *I*	NE *D*	SE *I*	SE *D*	SW *I*	SW *D*	NW *I*	NW *D*	Probable *Et*
1	1·0	9·7	10·9	17·0	13·3	13·8		22·6	−3·1	26·7	0·0??	24·7	−2·9??	27·7	−3·7??	20·5
2	7·6	14·1	12·9	11·3	12·9	20·4		23·1	1·1	30·1	−3·1??	29·4	2·9??	33·2	−5·9??	31·8
3	6·1	12·0	10·2	12·5	9·3	17·1		—	15·6	—	19·5	—	17·1	—	14·4	22·8
4	9·1	4·2	5·8	7·5	5·1	14·7		—	9·4	—	7·5	—	10·4	—	6·9	17·6
5	11·4	8·8	14·5	9·4	10·3	22·2		30·8	−24·4	24·8	−14·3??	21·0	−10·5	31·4	18·6??	19·8
6	13·5	7·8	11·2	10·8	10·7	23·7		25·5	−12·8	23·4	−6·8??	25·8	−12·7?	29·0	−4·5??	26·4
7	7·4	8·6	9·6	4·6	16·6	14·0	20·5	—	15·8	—	16·3	—	12·2	—	13·3	21·9
8	15·8	2·6	7·3	6·4	−0·1	20·3	19·4	—	−2·6	—	−5·4	—	−3·2	—	2·3	13·6
9	—	15·8	24·9	12·9	28·1	14·4	26·5	23·0	0·1	18·7	(10·8)	16·8	6·7	24·7	4·4	26·3
10	25·2	−5·7	−7·2	2·0	−7·1	23·4	18·0	—	−6·2	—	−4·0	—	−2·0	—	−4·8	21·0
11	38·7	−17·8	−13·9	−16·5	−5·0	21·5	28·3	—	−7·6	—	−14·4?	—	−15·6?	—	−10·8??	23·7
12	2·0	15·7	17·1	18·2	21·8	19·0	21·4	—	22·3	—	29·2	—	28·5	—	27·7	28·9
13	9·4	11·4	9·8	1·7	18·9	16·0	23·8	—	8·8	—	8·1	—	7·2	—	4·2	16·5
14	36·9	−29·6	−13·7	−21·0	−29·2	11·6	15·5	—	−14·9??	—	−22·7	—	−21·0	—	−14·0??	15·0
15	—	20·3	12·9	12·4	20·1	16·4	16·5	—	−0·5??	—	15·7	—	7·8	—	−2·1??	11·8
16	8·9	11·6	6·0	8·6	13·7	18·9	18·7	—	19·5??	—	17·6	—	19·1	—	17·1??	27·2

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because there is no reason for challenge: those with a single question mark are accepted and used though they might be challenged as including a drainage component: those with two question marks are rejected.

Periods 14 to 16 are in a different category. The confused results in Periods 14 and 15 have already been discussed: looking at the water balance for the NE I site in Period 15 presents the absurdity that in a period without rain, during which unirrigated neighbours evaporated 16 mm of water, a healthy stand of sugar beet used no water whatever (actually gained a little!). Within expected scatter, the balance at the NW I site is equally absurd. What went wrong in unknown, but these two sets of I site readings for the last three periods will be rejected simply because they are absurd in relative values, period to period. In total, over the three periods treated as one, the values of $(\sum R + D)$ are 50 (NE), 56 (SE), 52 (SW), 51 (NW) mm, and in rejecting two of these for the evaporation estimate it is the larger values (SE and SW) that are retained.

TABLE 5(I)

Water balance (mm): Sugar beet, 1970

	Period	E_O NE, SW	E_O SE, NW	E_I (selected)	E_T
1	5–16/6	14		20	39
2	16–23/6	34		52	62
3	23–29/6	51		75	82
4	29/6–3/7	66		93	94
5	3–10/7	88		112	112
6	10–16/7	112		139	129
7	16–23/7	126	132	161	145
8	23–30/7	146	152	174	159
9	30/7–5/8	161	178	201	176
10	5–12/8	184	196	222	190
11	12–26/8	206	225	245	216
12	26/8–1/9	224	246	274	228
13	1–10/9	240	270	291	243
14	10–21/9	252	285	306	259
15	21–28/9	268	302	318	266
16	28/9–12/10	287	321	345	279

Full season balance

		O NE	O SE	O SW	O NW	I NE	I SE	I SW	I NW	Nominal (or average)
R		193	193	193	193	193	193	193	193	193
I		—	—	—	—	125±10	124±5	118±6	146±6	121
D	0–90	60	88	76	96	12	38	30	15	(24)
	0–150	90	118	98	139	20	58	49	30	(39)
$R + I + D$	0–90	253	281	269	289	330	355	341	354	(338)
	0–150	283	311	291	332	338	375	360	369	(353)

Processed $E_O = 304$ mm
Processed $E_I = 345$ mm
$E_T = 279$ mm

Under 'Nominal' in the whole season balance, Table 5, the average values of D show the extra decrease in water content in the layer 90 to 150 cm as 15 mm, i.e. half that at O sites. This could be the result of plant activity: it could be drainage. In the transfer to Fig. 19 it is assumed to be plant activity, and is counted as evaporation.

On Fig. 19 the coherence of the points for I sites is good, and the slope of the full line drawn is 1·3. At O sites the record has three aspects. Up to Period 6 the quadruplicate measurements agree very well and for Periods 4, 5 and 6 the dashed line drawn is parallel to the full line for I sites. After Period 6, the divergence of averages for duplicates is

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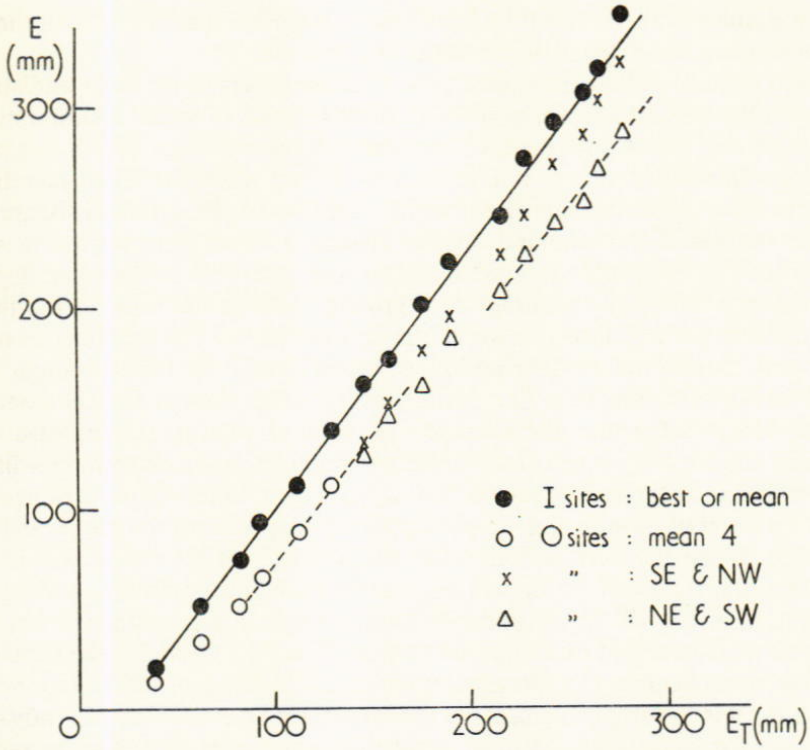

FIG. 19 (I). Evaporation, sugar beet 1970. Full points are averages of the good or best at I sites: open points are averages, of 4, at O sites, until crosses give average of SE and NW, and triangles give average of NE and SW.

clear, and it is thought that the set of crosses is a little misleading because the measurements of drying were probably over-estimates produced by preferential drying close to an access tube. The set of triangles could be equally misleading in the opposite sense for the opposite reason: the slope of the upper dashed line is 1·2, and in this group of periods when rainfall was adequate to meet all expected transpiration requirements the slope at O sites should have been the same as that for I sites. Statistically, if it is assumed that what was lost on the triangles was gained on the crosses, the mean (of four) value at the final set of measurements (at $\sum E = 304$ mm) lies on the continuation of the lower dashed line, and, hence, from Period 3 to Period 16, the water use by the two sets of plants was the same. The major inference to be drawn—in the context of meter accuracy and interpretation of hydrological meaning—is that the deep drying (90 to 150 cm) at both O and I sites was almost certainly caused by plant activity and not by slow drainage.

The difference between the sites was almost completely established by the end of Period 2, and, as noted, this is not a plant effect. The extra evaporation in the first two periods was from the bare soil between the plants, wetted by irrigation.

Discussion and conclusion

The meter is reliable, and it is precise enough to yield small differences that may be important in either the physics or the plant physiology of soil water. At its best, in the barley results for Periods 4, 6 and 7, the accuracy is better than that of the commercial water supply meter used to measure the total volume of water applied over the whole of the irrigated areas. To achieve the best, two conditions must be satisfied, one associated

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with the mechanics of the access tube installation, the other associated with the crop, and both dependent on the physics of the scattering process.

The first condition is that the access tube must be a very tight fit in undisturbed soil, but even with the best attainable, as in 1970, there is a risk of water accumulating around the bottom of the access tube to give spuriously large readings. When this occurs it is usually easily detected, but it is not so easy to decide when the effect has disappeared and readings have again become trustworthy. Because of the artificial fissure produced between the outside of the tube and the soil around it, there must always be a tendency for this part of the soil profile to start a little wetter than it is at the same depth further away, a tendency that may encourage root growth towards the tube during the first dry period of the summer and lead to anomalous drying within a few centimetres of the tube. In wetter soil, horizontal re-distribution of water could be rapid enough to restore horizontal uniformity, but in a dry period lasting long enough for the roots to grow significantly towards the tube the average soil water content could decrease so far that the hydraulic conductivity is too small to permit rapid enough horizontal re-distribution: the meter response at the end of such a period will be an under-estimate of average water content at the level of monitoring, i.e. the apparent evaporation for the period will be an over-estimate. When the next period is wet the formerly driest region will be re-wetted most, the apparent gain of water will be greater than the horizontal average, and the apparent evaporation will be an under-estimate. The compensation will not always be complete, but it means that on diagrams such as Figs. 8, 13 and 19, the envelope of the minima may come nearest to representing the seasonal trend of total evaporation.

This, though it is a crop problem, is not the important crop problem, already considered in some detail for sugar beet. At most, only two beet plants can affect meter response, at least near the surface. This difficulty of choosing a representative single site would arise with any other method of monitoring, but it is a little more acute here because of the neutron meter's extra sensitivity to changes immediately outside the access tube.

The uncertainty justifies a final note of caution. In Figs. 8 and 13 the slopes of the lines of E against E_T are both near 1·15: in Fig. 19, for sugar beet, the slope is near 1·3. The difference is probably real, but it may not be as great as this. During processing some readings have been rejected for reasons given in the text, and in amounts that are clear from the tables. In those retained, wherever there was doubt about a drainage component (and sometimes when there was near certainty that it occurred) it has been assumed to be zero, i.e. the quantities in the numerators of the ratios 1·15 and 1·3 are probably too big, not because of a defect in the meter but because of the interpretation imposed on its readings. The meaning and importance of this ratio—to be given the symbol κ in Part II—will be discussed at the end of Part III when about 25 values will be available for inter-crop comparisons. It is enough to note here that for well-watered tall crops, $\kappa > 1$, as expected.

Other aspects of the 1970 results, as they affect meter performance, plant activity or soil properties, were discussed as they arose, and are brought together in the summary. Only one needs a little more detail.

Four profiles were monitored on 4 May (barley), another four on 6 May (beans), and eight on 5 June (sugar beet), when the deficit under the barley had increased by about 65 mm. In the May group of eight, the range was from 608 to 744 mm, with an average of 670 $\pm$ 50 mm, and in the June group of eight the range was from 619 to 753 mm, with an average of 668 $\pm$ 52 mm, fortuitously the same in at least two of the attributes. This degree of scatter in contemporary measurements at neighbouring sites is at least ten times the worst acceptable in periodic differences at a single site, and utterly precludes soil sampling as a field method of calibrating the meter.

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