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Irrigation Decisions Simplified with Electronics and Soil Water Sensors

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ABSTRACT

Two simple, inexpensive systems use electrical resistance measurements to provide useful, immediate information to assist decisions made on irrigation water application. In one system a microprocessor-based circuit coupled to a programmable calculator provides an on-site estimate of the time until the next irrigation will be required, based on field data and an operator-supplied parameter. The second system simply signals the arrival of the wetting front at any location in the soil by giving a visual indication, such as raising a mechanical flag. The microprocessor-based circuit measures and stores the resistance of four gypsum blocks once a day. The program in the portable calculator accesses this information and uses it to extrapolate the soil drying rate to predict the number of days until the next irrigation. By restricting the microprocessor circuit to data acquisition only and putting all number-handling routines into the calculator program, the cost and complexity of the microprocessor circuit is minimized, whereas maximizing the programming flexibility. This makes it feasible to install a number of these devices at different locations, all serviced by the same portable calculator.

The water infiltration circuit intermittently scans eight sets of stainless steel electrodes to locate the soil wetting front during irrigation. When the resistance across the electrodes decreases, signaling the arrival of the front, the circuit trips a spring-loaded flag. This provides a visible sign that the wetting front has reached that point in the soil. The equipment worked well. When irrigation was required in six or fewer days, the microprocessor/calculator system made correct predictions 85% of the time. An example of how easily any irrigation scheduling method may be converted to the microprocessor/calculator system is presented.

Additional Index Words: **water management, irrigation automation.**

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THERE ARE TWO general strategies for irrigation management. One uses high-frequency applications (generally $\leq$ 3 d), and the other relies on soil moisture storage and intermittent applications of water (generally $\geq$ 7 d). Electronic controls and soil water sensing instruments show promise for precise management of high-frequency irrigation (Phene et al., 1981). We report here our experiences using two specific types of circuits and sensors to make decisions for intermittent irrigations that may be separated by a few days or several weeks.

We have previously shown (Cary, 1981) that gypsum blocks placed in crop rows at the 0.15-m depth can be used to predict when irrigation is needed. We then developed and field tested a microprocessor/calculator system that reduces the resistance readings of the gypsum blocks to an average soil water matric potential at the field site. To address the problem of deciding when to end water application, we also field tested a detector circuit that indicates the location of the wetting front in soil during irrigation. We discuss here these circuits and the results of the field testing.

Irrigation decisions based on soil water potential measurements at the 15-cm depth and electrodes that detect the soil wetting front require much less sophistication than the complete water balance methods developed in recent years (Jensen, 1973; Wright and Jensen, 1978). They are, however, fundamentally related to the water balance method. The low cost and simplicity of equipment to make these decisions should lead to their acceptance as practical, on-farm management tools.

METHODS

Four sites on the Snake River Conservation Research Center were chosen to test the gypsum block-microprocessor/calculator system. The soil is Portneuf silt loam (coarse-silty, mixed, mesic Durexerollic Calciorthid). Representative sites were selected in fields of bluegrass sod (*Poa pratensis*), corn (*Zea mays*), sugar beets (*Beta saccharifera*), and barley (*Hordeum vulgare*).

Four blocks were placed 2 to 3 m apart and 0.15 m deep in the crop rows at each location. The leads were buried below the cultivation level and attached to the circuit box. The only environmental protection afforded the equipment was a plastic bag to prevent excessive moisture buildup in the boxes and some shading to avoid heating from direct sun on the boxes. The blocks were not individually calibrated but were checked for uniformity at saturation.

A diagram of the microprocessor-based circuit and a flow chart of its program are shown in Fig. 1 and 2. Details on the hardware and software are available from the authors. This circuit measured and stored in memory the resistances of the four gypsum blocks once a day. After the first 10 d, the earliest record was erased to make room for the current day's data, so the memory contained only data for the most recent 10 d.

We used a HP-97S programmable calculator with a Hewlett-Packard[3] parallel interface to process information from the microprocessor circuits into usable form. The calculator program found the average block resistances for each day and converted them into water potentials. The average daily potentials were then fit to an empirical function describing the soil drying rate. When the fitting was complete, the program printed the present soil water potential. The operator then entered the water potential that must be reached before irrigation and the calculator, extrapolating the drying rate curve, predicted the number of days until that potential should be reached. The system thus gave on site predictions of upcoming irrigation dates any time the operator used it.

Block resistances were first corrected for temperature with the relation previously described (Cary, 1981), then the soil water matric potentials and days until irrigation were determined from the following relations:

$$\Upsilon = 1.808 \times 10^{-2} R + 136.3 \ln R - 4.614 \sqrt{R} - 800 \quad [1]$$

and

$$\Upsilon = A\, t^n + B \quad [2]$$

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[3] Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product listed by the USDA.

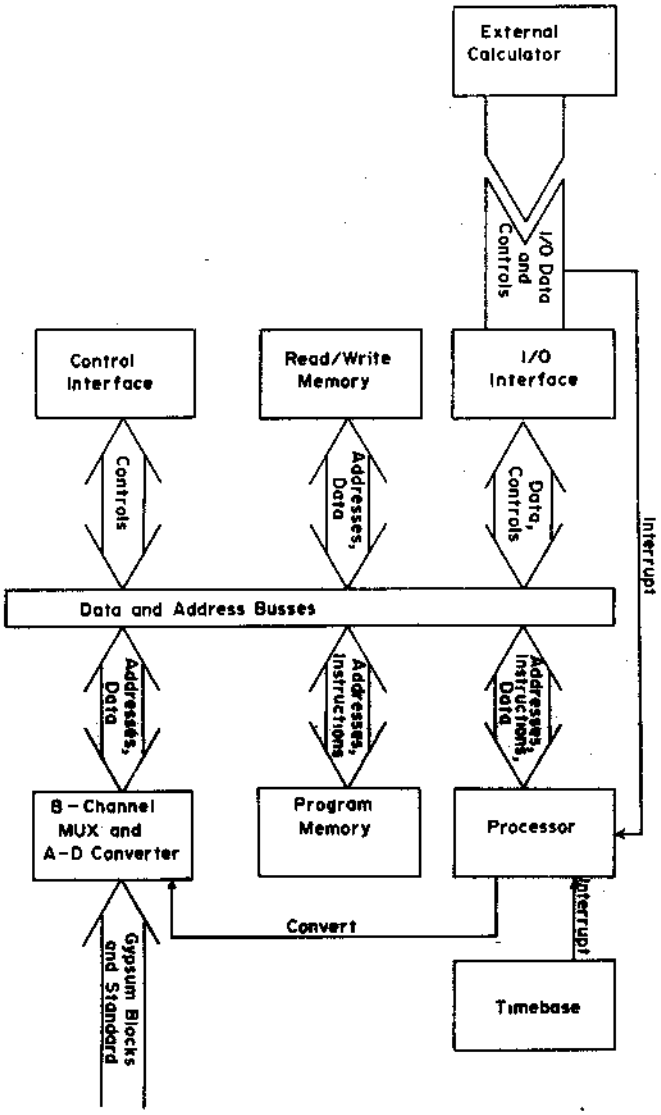

Fig. 1—A block diagram of the microprocessor based data gathering circuit for the gypsum blocks.

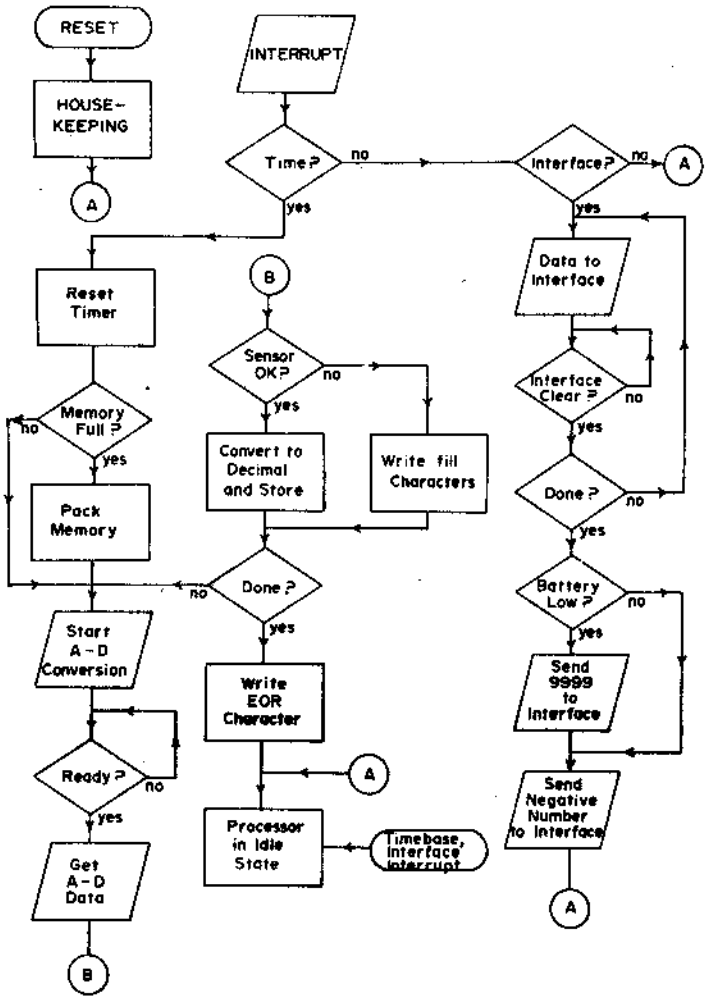

Fig. 2—Flow chart for the software program used by the circuit shown in Fig. 1.

or

$$\Delta t = \left(\frac{\Upsilon_{irr} - B}{A} \right)^{n^{-1}} - t \,, \qquad [3]$$

where Υ is the soil water suction, i.e., the negative matric potential in kPa, R is the resistance of the block, t the days since the last irrigation or rain, Δt the number of days from the present until the soil suction will reach Υ_{irr}, which is the specified suction to begin irrigation, n is a constant that depends on soil composition, texture, and depth, B the soil suction on day $t = 0$, and A the slope of the straight line through the measured points (Υ,t^n).

The calculator program requires data from a minimum of four consecutive days of soil drying before it makes an irrigation date prediction. If soil wetting occurs after this minimum time, the program calculates the slope, A, of the drying curve previous to the wetting and uses this for interim predictions until another four consecutive days of drying are available. The number of days, t, is counted from the day the suction last decreased, or taken as 10 if no decrease occurred in the 10 days' data available.

Two approaches to estimating t from block resistances were evaluated. In one, a linear regression of the data points (Υ vs. t^n) was done to get the best fit values of A and B. These were then used in Eq. [3] to obtain Δt. The second approach was to use Υ at $t = 0$ for B in Eq. [2], with the present day's values of Υ and t to solve for A. A and B were then used as in the first approach in Eq. [3] to find Δt. In both approaches, n was assigned values of 2, 3, and 4 to find which value gave the best predictions for our particular soil.

Figure 3 is a block diagram of the circuit used to detect the location of soil wetting fronts during irrigation. The electrodes of Fig. 4 are used with this system. The electrodes were located in the dry surface between irrigation furrows and the detector circuit monitored the resistance changes in an array of eight such electrodes.

Electrical resistance of dry soil between the electrodes drops by several orders of magnitude when wetted. The detector circuitry trips a mechanical spring-loaded flag when these changes in the array are of sufficient number and magnitude. The set point of the circuit is adjusted before each irrigation so that it is just less than the lowest resistance found among any of the eight electrodes. The thumbwheel switch is then set on the number of electrodes that the operator wishes to be wet before the flag will trip. This choice may vary from only one out of the eight to all eight of the eight electrodes, allowing the operator to adjust for some of the soil's variability.

Once a minute the detector circuit scans the electrode array, compares the electrode resistances to the set-point resistance, and counts the number of electrodes with resistance

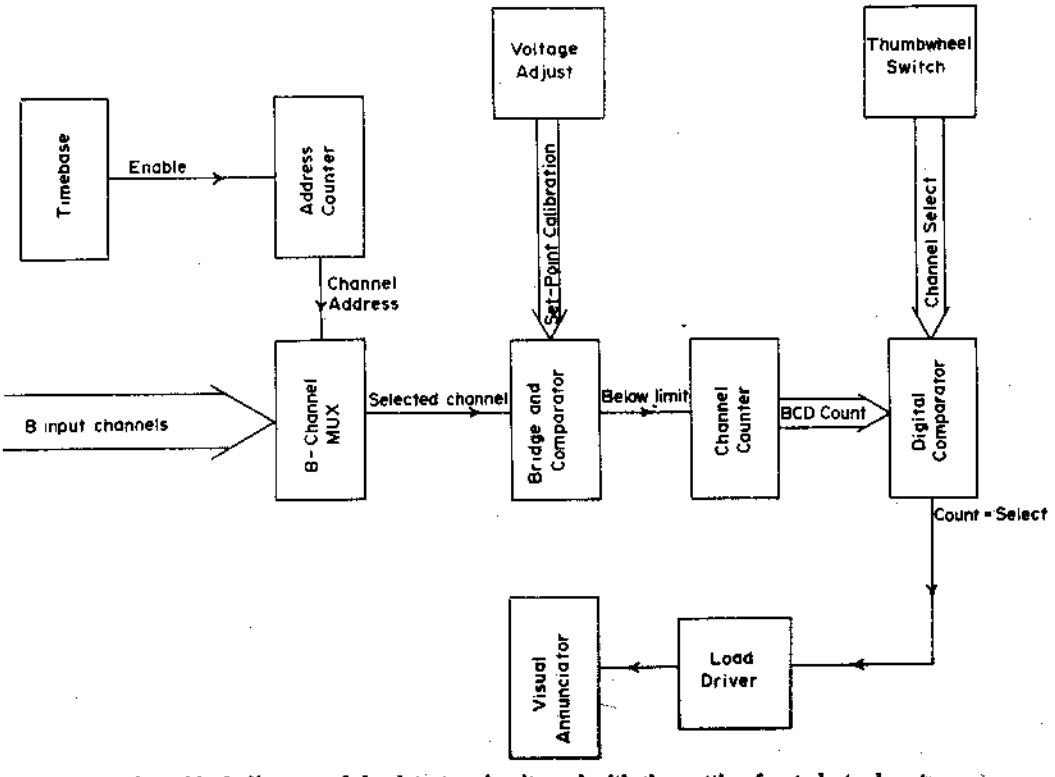

Fig. 3—A block diagram of the detector circuit used with the wetting front electrode sets.

below the set point. When the number of electrodes so counted is equal to or greater than the number set in the thumbwheel switch, the flag trips to alert the operator to the arrival of the wetting front at that location in the soil.

RESULTS AND DISCUSSION

Deciding When To Irrigate

Gypsum block resistances measured with the data collection circuit are several times larger than those measured with a laboratory AC bridge, as shown in Table 1. The data circuit uses a single square-wave pulse a few microseconds wide to make its measurement so that capacitive impedance in the moist blocks is less significant than with the bridge. A fixed resistor shows about the same value for both methods of measurement. The capacitive difference is accounted for in Eq. [1] by using different constants than those for AC bridge measurements (Cary, 1981). Measurements of the same block with the data circuit, repeated every minute under constant conditions, do show random changes with a coefficient of variation of 1 to 2%. There are no changes when a fixed resistor is measured repeatedly.

The gypsum block-microprocessor/calculator system performed satisfactorily in field tests. Irrigations of sugar beets were scheduled using the system and the yield was well above average due in part, of course, to favorable weather and good management practices under the direction of John Carter. The barley, scheduled by judgment of the station's irrigator, was occasionally water stressed. The bluegrass lawn was kept wetter than necessary, being irrigated on a fixed schedule arranged by the grounds foreman.

Dale Westermann scheduled the irrigation of the corn for maximum yield using tensiometers at 0.45 m, his previous field experience, and other local research results. Figure 5 shows the soil matric potential record for this field. The dashed line beginning at day 253 is a projection of the curve given by Eq. [2], although it was not actually followed due to the onset of rainy weather. These results show that the best local recommendations for irrigating corn on this field can be closely duplicated by irrigating when the gypsum

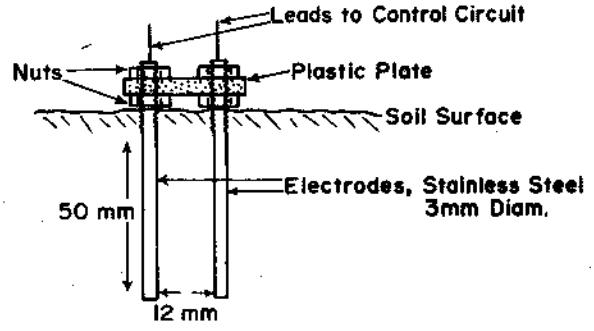

Fig. 4—A cross-section diagram of an electrode set used to detect the horizontal wetting front near the soil surface.

Table 1—The resistances of three gypsum blocks and one fixed carbon resistor measured with an AC bridge using two different frequencies compared with the resistance measured with the microprocessor-based circuit that used a short DC pulse.

Block	1000 Hertz	85 Hertz	DC pulse	Matric potential
	ohms			kPa
1	340	432	2028	−55
2	550	640	2624	−75
3	–	2105	6690	−120
Resistor	1110	1110	1255	–

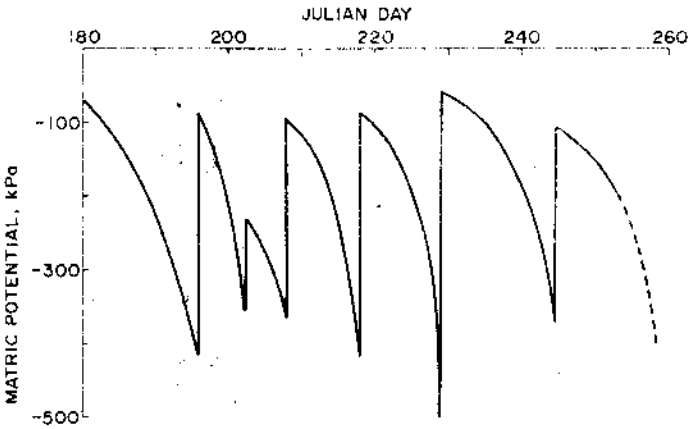

Fig. 5—Matric potential record measured with gypsum blocks at the 0.15-m soil depth under *Zea mays* (100 kPa = 1 bar).

blocks indicate a soil water suction of 400 kPa at a 0.15-m depth.

Throughout the 1982 growing season the system was used at 3- or 4-d intervals to predict the number of days until the soil water suction would reach 400 kPa in the three row crops. A limit of 200 kPa for Υ_{irr} was used for the grass because of its frequent irrigation. The results are shown in Fig. 6.

As noted in a previous study (Cary, 1981), no matter what method one uses, an irrigation prediction cannot be more accurate than ± 1 d because of the soil variability inherent in all fields. This means that all points falling within the envelop of dashed lines in Fig. 6 are sufficiently accurate. Points outside the envelop were due mainly to weather patterns that changed the slope of the drying curve after the prediction was made, and a few were due to predictions made shortly after irrigation (1–3 d) that were based on data from the previous drying cycle.

Irrigation prediction dates as shown in Fig. 6 for $n = 3$ were also plotted for $n = 2$ and $n = 4$. The results were summarized with a linear regression analysis (Table 2). The best correlation between predicted and observed irrigation dates occurred when $n = 3$ was used in Eq. [3]. Predictions using only observations of Υ at $t = 0$ and the present day's value of Υ to find A and B from Eq. [2] did not differ significantly from predictions using A and B found by linear regression of all the data in the interval between $t = 0$ and the present day. Values of $n = 2$ and $n = 4$ reduced the longer-range accuracy of the predictions, but of course they did converge to the correct answer as the irrigation date approached. The temperature corrections for gypsum block resistance had a negligible effect on the accuracy of the predictions.

How Long Should the Water Application Last?

Complete automation of irrigation requires some rational method of ending the application of water. One approach is to irrigate for a fixed time using a timer to terminate the application. This works well with sprinklers and level border systems but is less satisfactory for furrow irrigation because infiltration rates change during the growing season. A practical alternative for surface irrigation is to end the irrigation

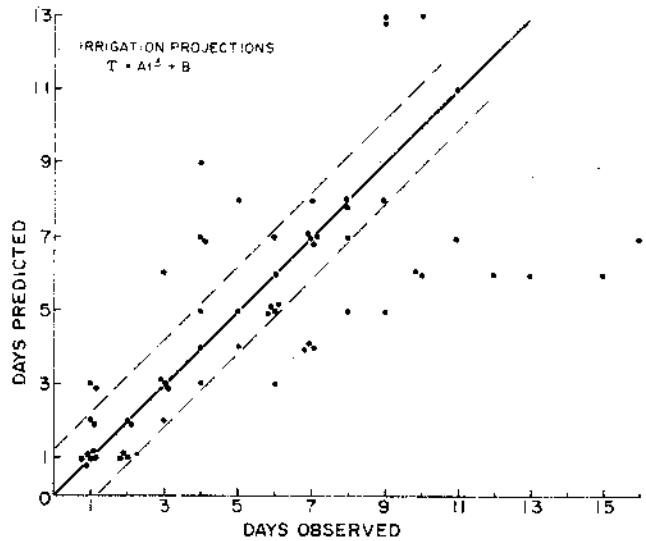

Fig. 6—Predicted vs. observed days until irrigation was needed. The individual points result from a variety of conditions discussed in the text.

when the water has soaked out to some predetermined location between the furrows. The advance of the wetting front as water infiltrates the soil is approximately proportional to the square root of time. Thus small variations in the leading edge of a ragged wetting front represents a significant difference in the amount of water applied. Using only one sensor to locate the wetting front would induce this same uncertainty into a control system. It is obviously better to use a number of sensors and a control that will turn off the water when the wetting front has reached a majority of the sensors. We found that when the soil surface is dry, terminating water application when five or six sensors out of an array of eight were wetted worked well. The sensors were generally placed in the surface 0.05 m of soil near the lower end of the field at locations we wanted the wetting front to reach before ending the application of water.

We also explored the use of longer electrodes made from stainless steel welding rod and insulated with heat shrinkable tubing except for 0.05 m of the tips. These were pushed down to 0.3 m to detect the arrival of wetting fronts at that depth. Generally, the soil at 0.3-m depth prior to irrigation is not nearly as dry as the soil surface, so the change in resistance at this depth is not as pronounced as at the surface when the

Table 2—A linear regression analysis of the effect of three values assigned to n in Eq. [2] on the relation between observed vs. predicted irrigation dates.

	Ideal	$n = 2$	$n = 3$	$n = 4$
Intercept	0	2.30	1.30	1.10
Slope	1	0.98	0.69	0.54
Correlation coefficient	1	0.60	0.73	0.69

Table 3—Resistance in ohms of stainless steel electrode sets at the 0.3-m depth at two similar field sites only 20 m apart.

	Probe numbers								%
Site	1	2	3	4	5	6	7	8	Water, kg kg⁻¹
A	4850	5200	5250	5800	5900	6100	6200	6600	23.7
B	2300	2500	2600	2800	3200	4400	4500	5700	22.5

wetting front arrives. Typical electrode resistances under sod in the Portneuf silt loam are shown in Table 3. This control uses the same type of resistance measurement that the gypsum block control does, so the resistances are higher than measured with an AC bridge. Variability between the electrode sets is rather large.

Suppose the set point of the circuit is adjusted to 2200 ohms under the conditions of Table 3 before an irrigation. As the wetting front reaches 0.3 m, the electrode resistances would all fall, but because the 23% water content is near field capacity, some of the resistances may not fall below 2200 ohms. Consequently, one has to rely on a smaller number of the eight electrodes being wetted to be reasonably certain of always detecting the wetting front. This reduces the value of the detector in accounting for soil variability when the electrodes are used at greater depths. This problem is not as critical for most applications as it might seem, because the sensors are always installed at a shallower, and consequently drier, depth than the depth of soil one wants to wet since the wetting front continues to move downward for some time after the termination of irrigation.

To get a reliable indication of wetting front arrival in moist soils, it appears that the set point of each electrode pair should be adjusted individually to accomodate the soil variation. To accomplish this we developed a simple, inexpensive circuit using a triac, a 9-V transistor battery, one pair of electrodes, and a spring-loaded flag. The electrodes were positioned in the soil, and a variable resistor in parallel with them was adjusted until the circuit was just ready to trip the flag. Since only one set of electrodes is involved, this adjustment makes the unit quite sensitive to small decreases in soil resistance as the wetting front arrives. As a further refinement, a timing circuit may be added to energize the detector only once every two minutes to prolong battery life. The whole unit, including hardware, can be assembled for about $10 in parts. This makes it feasible to use several units at different locations in the field to get a better average picture of when the wetting front reaches a given depth.

Transferring Water Management Technology

To predict irrigation dates using the gypsum blocks at the 0.15-m depth, one must know how great the soil water suction can become without reducing growth of the crop in question. This will depend on soil texture and depth as well as climate and stage of growth. In spite of all these variables, it is quite easy to obtain the information needed. For example, we knew how to irrigate corn to get maximum yield using tensiometers at 0.45 m. Growing the crop one summer according to these best available recommendations while simultaneously recording the soil suction at 0.15 m with the blocks and data circuit produced the information shown in Fig. 5. The curves were then used to obtain the best-fit value of the soil constant n and the optimum value of Υ_{irr} in Eq. [3] for the various development stages of corn grown locally. As a result, we can now schedule irrigation for corn using Υ_{irr} = 400 kPa and n = 3 in Eq. [3] after only one growing season's experience. Best local recommendations for irrigating a crop in another area can be similarly converted to use with the microprocessor/calculator system. One growing season is needed to make the transition, but it produces a simple and reliable system requiring very little operator training. It should favor rapid transfer of the best irrigation technology to commercial growers.

The irrigation management approach we used does not necessarily require that the soil profile be completely filled with each irrigation or that the operator know how much water is applied. It is important that the water be applied uniformly and that water logging or deep leaching of nitrogen does not occur. Use of the inexpensive electrodes to locate the wetting front during irrigation helps avoid excessively large applications that lead to these problems.

There may be coarse-textured, saline, or other soils with special properties that will not be amenable to gypsum block water suction measurements. In these cases one might use the ceramic sensors described by Phene et al. (1981) or the leaf-air temperature difference method (Idso and Reginato, 1982), both of which are compatible with a microprocessor-based data collection and prediction system such as we describe here.

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