IRRIGATION SCHEDULING WITH SOIL INSTRUMENTS: ERROR LEVELS AND MICROPROCESSING DESIGN CRITERIA

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Two criteria for deciding when a crop should be irrigated are: (1) the depletion of water in the root zone to some predetermined amount, or (2) the decrease of water potential at some given depth to a predetermined level. The value one chooses for either of these criteria to indicate that irrigation is needed will depend on soil properties, crop rooting characteristics and stage of plant growth. Functional relations between these two criteria and production are not yet known quantitatively, thus one cannot say that either approach is inherently better than the other. The effective application of either requires experience and judgment.

Recent years have seen significant progress in scheduling irrigation using meteorological data to calculate the depletion of water in the root zone. The daily potential evaporation from a full cover reference crop can be calculated within a few percent using measurements of air temperature, humidity, solar radiation and wind run.' Given an appropriate crop coefficient curve, the evapotranspiration can also be estimate and the soil water depletion known with varying degrees of accuracy. As an alternative, the rate of soil water depletion may be directly measured with a neutron meter or by gravimetric soil sampling. Gear et al. (1977) used a neutron meter to measure soil water on successive dates and projected soil water depletion with a straight line to a level where replenishment would be needed. This gave estimates of the number of days until irrigation.

Tensiometers, resistance blocks, thermoconductivity sensors, psychrometers and related instruments have been occasionally used or proposed for use in automatically starting irrigation at some given water potential. Tensiometers and gypsum resistance blocks have been available for many years to help decide when the soil should be irrigated. Fischback (1978) reported results of scheduling the irrigation of corn by several different methods including resistance blocks and a meteorological approach. He tended to favor the blocks.

At the present time, a farm manager may schedule irrigation with soil water potential instruments. Based on experience, he will extrapolate the soil water change expected in the next few days, and arrive at a projected date for irrigation. The recent evolution of microprocessors suggests that a system might be designed that would automatically read soil water potential instruments and predict the day to irrigate using an appropriate algorithm. This could lead to a level of sophistication for predicting irrigation frequencies comparable to that developing for computer scheduling with microclimate data (Wright and Jensen, 1978).

The general patterns of change in soil water potential with time at a given depth are shown in Fig. 1.

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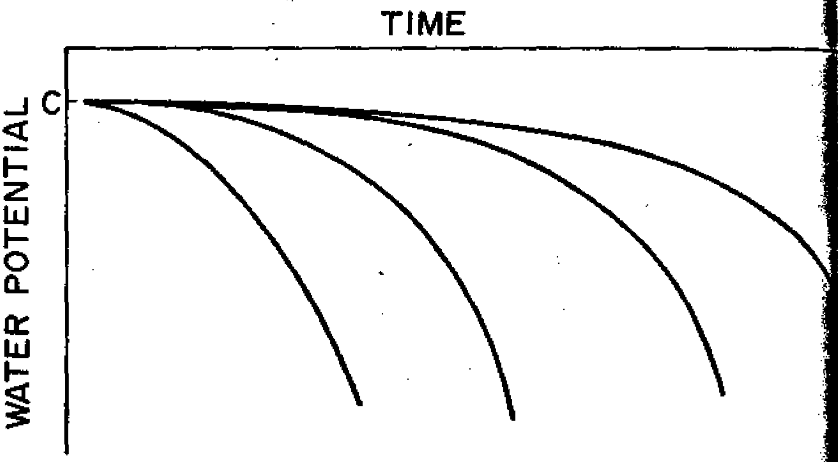

Fig. 1. A Family of Curves Illustrating the Effects of Various Evapotranspiration Rates on the Relation Between Time and Soil Water Matrix Potential, τ, at a Given Depth.

This family of curves can be approximated by the empirical function

$$\tau = At^n + C \qquad (1)$$

where t is time in days and τ is soil matrix potential in kPa. The constant n depends mostly on soil pore size distribution and the type of sensor, while the constant A is affected more by the rate of soil water depletion and C is the intercept at $t = 0$, i.e., immediately following irrigation. Note that Eq. 1 is a straight line using variables τ and $(t^n$ Consequently a value for n can be found for individual soils by measuring water potential changes during periods of evapotranspiration and choosing an n that gives the most consistent linear plots. Since the constants in Eq. can be calculated from appropriate data, a microprocessor could be programme to project irrigation by extrapolating time to some predetermined water pote tial. The feasibility of such an undertaking requires an analysis of the inherent errors with respect to the errors encountered in scheduling with microclimate data and with respect to the level of error that is practical f the grower. Specifically, it comes down to questions on the applicability o Eq. 1, the accuracy and reliability of soil water potential sensors, and the spatial variability of soil water in the field.

EXPERIMENTAL PROCEDURES

Data were collected during two growing seasons on four plots of Portneuf sil loam soil described in detail by Cary and Rasmussen (1979). Each plot was 2 meters long and 9 meters wide. Corn, beans, sugarbeets and grass were grown the first year; beans and sugarbeets followed the second year. The plots we irrigated with corrugates (except the grass which was border flooded). Each plot was sampled and instrumented on both ends such that data collection sit were about 170 meters apart.

There were 8 data collection sites the first season. Each had two permanent tensiometers at the 30-cm depth. There were commercial units with 45-cm lon plastic cylinders connecting the ceramic cups to vacuum gauges. Three gypsu resistance blocks[2] were also installed in the rows at the 30-cm depth within a 2-m radius. The resistance of each block was measured five days a week with a 1K Hertz electrical conductivity bridge. Soil temperatures around each set of blocks were also measured. Gravimetric soil water measurements at depths of 15, 30, and 45 cm were made from two cores taken about 2 m apart twice weekly at random locations in the rows near the blocks and tensiometers.

In the second season, the blocks were placed at both 15- and 30-cm depths and their resistances were measured twice a week. Three portable rapid response tensiometers[3] were also inserted twice weekly to measure water potential at the 30-cm depth. These tensiometers were placed at random not farther than 2 m apart in crop rows near the blocks.

Care was taken to irrigate the plots as uniformly as possible. Fertility and cultural practices were in accord with local recommendations and practices.

At the end of the growing season, 4 sites, 2 at each end of the field, were sampled, taking four undisturbed cores from each site. Slices were taken from these cores at the 26- to 34-cm depths and individual moisture desorption curves measured for each core. These data were used to calculate pore size distribution indexes by the method of Cary and Hayden (1974).

RESULTS

The gravimetric soil water measurements were used to assess the spatial variability within the plots and to compare the variability shown by the tensiometers and blocks. Methods of characterizing soil spatial variability are not yet very well developed, though this is being addressed by a number of soil scientists (Rao et al., 1979 and Western Regional Research Committee 155). In this case, the standard deviation was calculated for two or more observations that should have been identical. This value was divided by the mean of the observations to get the coefficient of variation. The average of all the coefficients of variation was then used to characterize the variability (Table 1). This approach reduces the dependence of standard deviation on the range of the data observations since the standard deviation of water potential increases rapidly as the potential becomes more negative.

The standard deviation of the water content increases as the water content increases, but as pointed out by Ben-Asher (1979), standard deviation in general for uniform soils is about 10% of the water content. Nielson et al. (1973) found average standard deviation of volumetric water contents between 5 and 7% in a field study, indicating a coefficient of variation range of 13 to 20%. Cassel and Nelsen (1979) also reported the coefficients of variation of volumetric water contents ranged from 8 to 25% in an intensive field study.

Entries 1, 3, 7 and 9 in Table 1 are measures of the short distance spatial variability of soil in the test strips. Average values of water potential from each of these local observation sites were averaged and their means used to characterize the overall spatial variability of the study area, i.e., entries 2, 4, 5, 8 and 10. Averaging several localized measurements to get means for characterizing the overall spatial variability reduces the error caused by the inherent variability of the measuring instrument as demonstrated

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[2] Beckman Instrument Company, Cedar Grove, New Jersey.

[3] Soil moisture probe Model 2900, Soil Moisture Equipment Corporation, Santa Barbara, California.

Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the U. S. Department of Agriculture.

Table 1. Coefficients of Variation Associated with Measured Values of Soil Water Potential, Water Contents on a Weight Basis, and Soil Pore Size Distribution Indexes.

Sample	Mean Coefficients of variation	Number of observations	Range of samples
1. Duplicate water contents from cores less than 2 m apart.	4.7%	1144	9 to 30% by wt.
2. Mean water contents from 8 separate field sites.	5.4%	582	10 to 28% by wt.
3. Pore size index from undisturbed samples at 30 cm within a 2-m diameter.	10.5%	16	2.4 to 3.6
4. Pore size index means representing 4 widely separated field sites.	5.9%	4	3.0 to 3.4
5. Water potentials from mean water contents at 30 cm representing 8 field sites.	20.6%	186	-20 to - 72 kPa
6. Calibration data of 28 individual gypsum blocks.	12.5%	136	-30 to -150 kPa
7. Individual blocks making up the means shown in Table 2, columns 2 and 3.	25.7%	306	-20 to -900 kPa
8. Data from columns 2 and 3 in Table 2.	16.6%	102	-30 to -800 kPa
9. Rapid response tensiometers separated by less than 2 m.	11.9%	384	- 5 to - 76 kPa
10. Tensiometer means, representing 4 widely separated field sites.	13.3%	106	- 1 to - 70 kPa

by the reduction in the coefficient from entries 7 to 8. The coefficient in entry 7 came from 12 blocks, 3 each at 4 widely separated sites in the study area. The coefficient in entry 8 was based on the means of 3 localized bloc at each of the 4 separated sites.

Water potential was estimated from the gravimetric water content at the 30-c depth, assuming a single water desorption function, Fig. 2, for all four plo (entry 5, Table 1). The coefficient of variation of these potentials was 20.6% which was greater than the coefficient of variations of the potentials measured with blocks or tensiometers (entries 8 and 10). Consequently, it appears the inherent inaccuracies in measuring soil matric potential with gypsum resistance blocks or tensiometers may be no greater than the inherent spatial variability in the field. Particularly with blocks, the average resistance of several placed near one another may be used to reduce the effect of their inherent variability.

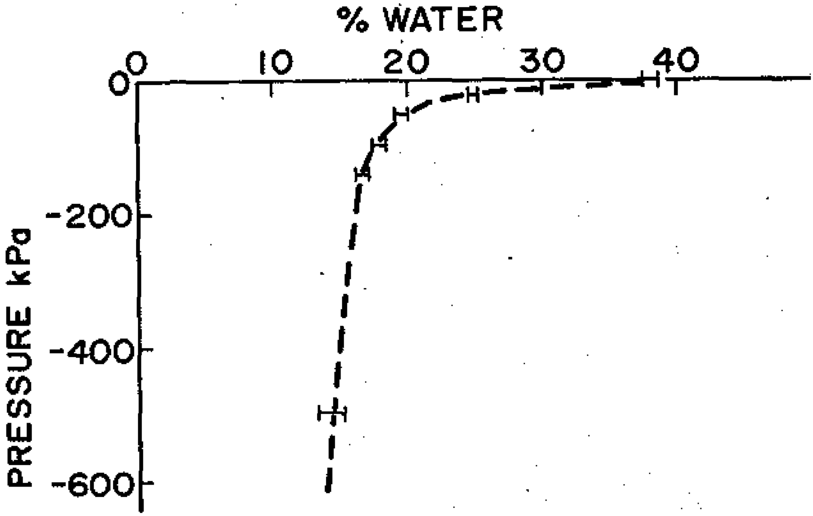

Fig. 2. Water Release Curve for the Soil Studied, Percent Water Dry Weight Basis as a Function of Pressure in the Desorption Chamber. Brackets Show the Spread of Mean Water Contents from the Four Sampling Sites. The Pore Size Distribution Indexes Associated With These Data are Given in Table 1.

DISCUSSION

Several problems associated with automating the tensiometers and blocks with a microprocessor to read out projected irrigation dates were noted during the experiment and analysis of data. The permanent plastic tube tensiometers were unsatisfactory for automation because they required weekly service and were sluggish when the soil was drier than -60 kPa. They had to be placed 30 cm deep to remain operative for at least the first two-thirds of some irrigation cycles. The rapid response tensiometers were better, but even they had to be recharged once or twice during the season. Their effective range was only down to a bit less than -70 kPa (elevation 1,130 m). Their mobility and rapid response time were advantages insofar as characterizing conditions in the field, but considerable care was required to install them, particularly when the soil surface was dry and slaked into the access holes.

The gypsum resistance blocks also have several inherent problems. They are temperature dependent. The empirical equation

$$R_{22} = [(T^{0.011} - 1)(T - 22) + 1]\,R \qquad (2)$$

was found from measurements made in a controlled temperature room. It was used to correct the observed resistance to the 22°C calibration temperature. A second empirical equation was then developed for the soil water potential

$$\tau = 0.0217\,R_{22} + 69.84\,\ln R_{22} - 3.245\,\sqrt{R_{22}} - 310.5 \qquad (3)$$

where R is the measured resistance in ohms, T is the temperature of the block °C and R_{22} is resistance corrected to 22°C.

Gypsum blocks also have some wetting and drying hysteresis that may be significant under transient soil water conditions. Problems were noted at the 30-cm depth when irrigation did not quite increase the potential to -30 kPa before rapidly falling again due to soil water extraction. In essence, the blocks did not always rewet to the level indicated by gravimetric samples. This problem was less at the 15-cm depth because the soil water content rises higher following rain and light irrigations allowing a more complete block response. As a consequence, blocks at the 15-cm depth passed through a wider range of water potentials during each drying cycle than blocks at the 30-cm depth or tensiometers at any depth. This is an advantage for automation and data reduction with a microprocessor.

The mean water potentials from the three temperature corrected blocks at the 15-cm depth are shown in Table 2 for the upper and lower ends of the beet and bean plots during the second season. The predicted lengths of the drying cycles are also shown at various times during each cycle for the lower and upper ends (columns 4 and 5). The predictions are from Eq. 1 taking $n = 3$, C (i.e., field capacity) as -30 kPa and using the average water potential from the three blocks on day, t, to find the value of A. With exception of the first few days following irrigation, this method predicted the length of drying cycles within one or two days of those observed, even though the cycles ranged from five to 25 days. This method requires only a portable nonpolarizing meter to measure the resistance of the blocks and a simple hand held programmable calculator. The manager must enter the resistance, number of days since irrigation, an estimate of the soil temperature at 15 cm, the field capacity, C, and the potential at which he wishes to irrigate. He will then receive the projected number of days until irrigation. This simple predictive method using only the current day block reading may encounter problems following a light rain that lowers the resistance but does not bring the blocks all the way back to field capacity. In this case some judgment will be needed by the operator concerning the appropriate value of A and t. With respect to the data in Table 2, the only significant rainfall during the growing season was 0.7 cm on May 23, 0.9 cm on June 18, and 1.9 cm on August 13-15. Irrigation can also be scheduled with a programmable hand held calculator using weather data (Kanemasu et al., 1978). However, daily weather records are needed for input as well as specific information on crop and soil conditions.

The last column in Table 2 gives the drying cycle length calculated from a linear regression of Eq. 1 using τ and (t^3) as variables. This method gives values for both A and C. Input data for each day was the mean potential of all six resistance blocks in the irrigation strip, in this case not corrected for temperature. Regression analysis was started after each irrigation. For fewer than five days, the length of the cycle was calculated from Eq. 1 taking time equal to one day, the current mean block resistance as C, and using the slope A from the previous cycle. Again, after the first few days, the regression method gave cycle lengths in good agreement with the observed values; i.e., the calculated values were generally within the limits of uncertainty due to spatial variation between the ends of the plot. Neglecting the temperature correction made no significant difference until September when the predicted cycle became several days too short. Soil temperatures had fallen to 12-14°C compared to 20-22°C throughout most of the summer. Possibly automation and storage of the daily block resistances for use in regression analysis would reduce the prediction error during the first few days following irrigation. In any case, using the regression analysis in a microprocessor that receives daily data input eliminates the need for operator judgment following a rain or light irrigation where the blocks do not go all the way back to a field capacity reading. The processor would treat any significant drop in resistance as the start of a new irrigation cycle and use the slope A from the previous cycle to project irrigation dates until a few days pass and provide a more current data base for regression.

Table 2. Predicted and Observed Lengths of Time Required for the Soil at 15 cm to Reach Various Water Potentials Following Irrigations for the Lower and Upper Ends of the Field.

Irrigation date and crop	Days after irrig.	Observed Potential, kPa		Predicted Number of days until the specified H_2O potential was reached		
		Lower end	Upper end	Lower end	Upper end	Combined
22 May Beets	7	- 33	- 33	22	22	-
	10	- 46	- 46	18	18	19
	14	- 83	- 83	17	17	18
	17	-110	- 91	18	19	18
Observed number of days for the H_2O potential to fall to the specified level of -120 kPa ⟶				18	19	
11 June Beets	1	- 29	- 35	-	4	28
	4	- 37	- 60	14	8	10
	8	- 49	- 71	19	15	17
	11	- 63	- 84	22	19	21
	15	-118	-167	22	19	21
	18	-205	-308	21	18	20
	21	-389	-470	19	18	18
Observed number of days for the H_2O potential to fall to the specified level of -300 kPa ⟶				20	18	
03 July Beets	2	- 37	- 54	8	5	22
	6	- 87	-112	11	10	11
	10	-320	-310	11	11	11
	14	-799	-557	11	12	12
Observed number of days for the H_2O potential to fall to the specified level of -400 kPa ⟶				11	12	
18 July Beets	2	- 41	- 57	6	5	14
	7	- 79	- 94	14	13	16
	12	-297	-253	13	14	15
	15	-770	-473	12	14	13
Observed number of days for the H_2O potential to fall to the specified level of -400 kPa ⟶				13	14	
10 August Beets	5	- 39	- 49	17	9	18
	10	- 53	- 70	25	21	26
	14	-100	-117	24	23	24
	18	-212	-191	23	24	22
	21	-311	-234	23	26	23
	25	-501	-370	23	26	23
Observed number of days for the H_2O potential to fall to the specified level of -400 kPa ⟶				23	26	
05 Sept. Beets	2	- 41	- 51	7	6	26
	5	- 47	- 67	15	12	16
	12	-173	-117	18	21	24
	16	-196	-220	23	22	22
	23	-378	-329	25	27	24
	30	-656	-457	27	31	25
Observed number of days for the H_2O potential to fall to the specified level of -500 kPa ⟶				27	32	

(continued)

Table 2. (continued)

22 May	11	- 62	- 60	12	13	-
Beans	14	- 69	- 63	15	16	15
	18	- 80	- 71	17	19	17
	21	-	- 74	-	21	18
Observed number of days for the H_2O potential to fall to the specified level of -75 kPa →				16	20	
01 June	1	- 41	- 47	2	2	44
Beans	4	- 56	- 59	7	6	8
	8	- 66	- 63	12	12	13
	11	- 73	- 68	16	16	18
	15	-111	- 87	17	19	16
	18	-171	-121	17	20	18
	21	-229	-132	18	22	18
Observed number of days for the H_2O potential to fall to the specified level of -150 kPa →				17	22	
02 July	3	-106	- 69	4	5	7
Beans	7	-254	-146	6	8	7
Observed number of days for the H_2O potential to fall to the specified level of -200 kPa →				6	9	
10 July	3	-103	- 66	4	5	10
Beans	7	-298	-141	6	8	8
Observed number of days for the H_2O potential to fall to the specified level of -200 kPa →				5	9	
18 July	2	- 59	- 54	3	4	10
Beans	7	-187	-206	8	8	8
	12	-601	-302	9	12	10
Observed number of days for the H_2O potential to fall to the specified level of -300 kPa →				9	12	
05 August	5	- 48	- 51	7	6	9
Beans	10	- 66	- 64	11	11	11
	14	- 71	- 71	14	14	14
	18	- 71	- 76	19	18	16
Observed number of days for the H_2O potential to fall to the specified level of -75 kPa →				21	17	

The error of one or two days in predicting cycle lengths compares favorably with the errors encountered in scheduling irrigation from daily climatic measurements. Jensen and Wright (1978) show prediction confidence limits of ± 1 day for irrigating alfalfa when the soil water content in the root zone is measured just after the irrigation cycle starts. If the soil water is not measured during the cycle, the confidence limits may be ± several days due to uncertainty of how well the soil profile was wetted.

Ultimately, the uncertainty of all prediction methods must be at least as great as the spatial variation of soil water on a field basis. Jensen and Wright (1978) reported using the neutron meter and measuring soil water to a depth of 75 cm with a standard deviation ranging from 0.7 to 1.1 cm of water. If this range of standard deviation represented the spatial variation in the field, the least uncertainty one might ultimately achieve in predicting irrigation would be ± 1 day, and then only during the midpart of the growing season when transpiration is high. If the soil water was measured gravimetrically as on the plots studied here that had a coefficient of variation of 5.4% and the volumetric water content was 25%, the uncertainty in 75 cm of soil would be 1 cm of water, also giving a minimum uncertainty of at least

± 1 day, and this was a uniform land area. In most practical cases the variability will be greater, indicating there is little to be gained from more accurate individual soil water measurements.

Automation of the gypsum resistance block method offers several potential advantages in predicting irrigation dates when compared to microclimate methods: (1) the block method converges to the correct prediction as time for irrigation nears, (2) it does not require a local crop calibration curve, (3) the amount of water added by irrigation and rain need not be known, (4) the block method appears to be adaptable to some areas where the microclimate approach is difficult to use, such as a shallow water table supplying part of the water for transpiration, and (5) the field truth data could be automatically collected and transmitted from the field making the block method less labor intensive. On the other hand the microclimate approach is well suited for estimating evapotranspiration from large land areas and so is a valuable tool for managing other problems related to soil water evapotranspiration.

A sensor whose resistance is more responsive to water potentials in the -10 to -30 kPa range may be needed in sandy soils. There are also potential instrument problems associated with saline soils that were not studied here. It is possible deeper placement of blocks might be better for some perennial crops having long irrigation cycles due to deep soil and root systems. Nevertheless, the 15-cm depth represents the surface soil zone with the greatest density of crop roots. Most of the nutrients are in this zone and in general, it is this soil volume that must receive optimum management if maximum production is to be achieved. The recommendations for the relatively shallow placement of the blocks as well as the preference for blocks over other soil water instruments for interfacing to a microprocessor are in agreement with the results reported by Shull and Dylla (1980).

CONCLUSIONS

Irrigation dates can be projected using Eq. 1 with gypsum resistance blocks placed in silt loam soil at the 15-cm depth. The accuracy of this method compares favorably with the present scheduling of irrigation from microclimate data. Technology exists to develop a fully automated system. Representative field sites would be instrumented with three to four blocks connected in series to a resistance measuring device that could, upon demand, transmit by wire or radio the resistance to a microprocessor in the manager's office. The microprocessor would interrogate each site daily and store its resistance. Upon demand, this information would be processed through Eqs. 1, 2, and 3 using the linear regression analysis for each irrigation cycle as demonstrated in the last column of Table 2. The only input required by the manager would be an estimate, ± 3°C, of the soil temperature and the water potential at which he wished to irrigate. The microprocessor would keep its own time, referenced to the abrupt decrease in block resistance that occurs during irrigation or rainfall. This type of system should be essentially maintenance free, requiring no labor other than installation of the resistance blocks after planting.

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