Field Test of an Irrigation Scheduling Computer Model

WAYNE S. MEYER* and GEORGE C. GREEN
Soil and Irrigation Research Institute, Department of Agriculture and Fisheries, Private Bag X79, Pretoria, 0001

Abstract

An experimental field test of the "USDA-Irrigation Scheduling Model" was carried out on a wheat crop at Roodeplaat near Pretoria during 1979. The model uses current meteorological data and a crop water use coefficient to predict the rate of evapotranspiration ET. A soil water balance is calculated and irrigations are forecast. Calibration for local conditions was made using results obtained during 1978.

The comparison of soil water depletion predicted by the model and that measured from soil samples showed good agreement. Grain yields from experimental plots which received the scheduled irrigations were not significantly different from plots which received irrigations according to the actual ET losses measured with a weighing lysimeter located on the same site. However, measured ET was 15% less than predicted ET which suggested that the scheduled plots received water in excess of their requirement.

Introduction

Scheduling of irrigation water involves estimating the time of application and the amount to be applied. In many areas the timing of irrigations is based simply on a rotational system or on a demand system. In the first case, either constant or variable irrigation amounts are given at regular intervals with little regard to climate variability. These systems inherently result in low irrigation efficiencies. The second system is usually based on a combination of experience and visual observation of both soil and plant characteristics. The criteria used in these demand systems are often qualitative so that quantification for the purpose of communication and management improvement are difficult. More direct methods of irrigation scheduling are available in the form of tensiometers (Streutker, 1978) and "Class A" pan crop factors (Green, 1977). These methods can be most satisfactory if applied at farm level by good irrigation managers.

The development of physically based formulae (e.g. Penman, 1963) to calculate expected evapotranspiration from a crop canopy using easily measured daily meteorological data has allowed greater precision in predicting crop water requirements. There can be no doubt of the need to implement such predictions at a farm management level as part of a physically sound system of irrigation scheduling.

This paper reports the results of using a computer model to schedule irrigations for a wheat crop grown under experimental field conditions at Roodeplaat. The model used is commonly known as the "USDA Irrigation Scheduling Model" and was developed by Jensen *et al.* (1970, 1971). Data obtained from field experiments using weighing lysimeters (Meyer and Green, 1979) was used to calibrate the model prior to its use during the 1979 season.

Materials and Methods

General outline of the model

Details of the model are given by Jensen *et al.* (1971) and it is sufficient here to give the general basis of the calculations. The model uses a basic water balance equation to predict soil water depletion D each day.

$$D = D_i + (ET - R - I + DR) \quad \ldots\ldots\ldots\ldots (1)$$

where D_i is soil water depletion for the previous day, ET is evapotranspiration, R is rainfall, I is irrigation and DR is drainage from the soil profile. All values are in millimetres of water.

The procedure first estimates daily potential evapotranspiration ET_p using the combination equation developed by Penman (1963).

$$ET_p = \frac{\Delta}{\Delta+\gamma}(R_n\text{-}G) + \frac{\gamma}{\Delta+\gamma}(a)(b+U)(e_s\text{-}e_d) \quad \ldots\ldots (9)$$

Where Δ is the slope of the saturation vapour pressure-temperature curve at the daily mean temperature, γ is the psychrometric constant, R_n is daylight net radiation, G is daily soil heat flux, U is total daily wind run, a and b are empirical constants, e_s is the daily mean saturation vapour pressure and e_d is the saturation vapour pressure at daily mean dew point temperature.

When ET_p has been calculated with values derived from daily meteorological data, actual ET if found as

$$ET = K_c\, ET_p \quad \ldots\ldots\ldots\ldots (3)$$

where K_c is a dimensionless constant derived empirically from the ratio ET/ET_p. ET in this case is the measured evapotranspiration from a well-watered crop. Two functions are used to describe the value of K_c through the growing season. The first function relates K_c to the proportion of time between the sowing date and effective cover date and the second relates K_c to the time between effective cover date and harvest date. These functions, by adjusting cover date and harvest date as the season progresses, can be made to partially account for year to year variability in crop development rate. The value of K_c is modified to account for decreased ET if soil water status declines below 30% of the maximum available (Meyer and Green, 1980b). A function to calculate the evapotranspiration from a wet soil surface for three days following rain or irrigation is used while $K_c \leq 1.0$. Total ET is thus the sum of crop transpiration and soil evaporation during this time.

Daily amounts of rainfall and irrigation are needed as inputs. Water applications in excess of the estimated soil water depletion are assumed to drain immediately from the soil.

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*Seconded from the Water Research Commission, PO Box 824, Pretoria, 0001.
Present address: CSIRO, Division of Irrigation Research, Private Mail Bag, Griffith 2680, NSW Australia.

The forecast date of irrigation will be the day on which

$$AD\text{-}D\text{-}\Sigma(\overline{ET}_c) = 0 \quad \ldots\ldots \quad (4)$$

where AD is the maximum depletion of soil water allowed at the stage of crop growth during the forecast period, D is the current depletion and $\overline{ET}_c$ is the expected average ET for each day during the forecast period calculated from $\overline{ET}_p.K_c$. The expected average potential evapotranspiration for the forecast period $\overline{ET}_p$ is estimated from a function which uses the time of the year to calculate maximum expected values of incoming radiation. On the day of a forecast irrigation the amount of water to apply is the estimated depletion adjusted for the expected efficiency of water application.

Input data for the model

A description of the necessary input data is given below and values of inputs used during the 1979 season are given in brackets.

Initial input data

(1) Number of regions and name of each region to be considered (1, Northern Transvaal).

(2) Maximum rate of evapotranspiration expected, and the Julian date on which it occurs. (10 mm, 355).

(3) Maximum daily solar radiation expected (32,4 MJ m^{-2}).

(4) Number of farms within each region and the number of fields on each farm which are scheduled (1,1).

(5) Julian date of sowing, effective cover (heading date in wheat) and harvest (166, 260, 310). Cover date and harvest date can be adjusted as the season progresses.

(6) Name of each farm and name of each crop (Roodeplaat Agrohydrology, Wheat).

(7) Maximum plant available water in the whole profile (230 mm).

(8) Functions to describe K_c for the crop concerned (see Fig. 1).

(9) Parameters to describe the annual variation of incoming solar radiation (137, 124), being the number of days before and after the day of maximum solar radiation (R_{max}) when a level of 0,37 R_{max} is attained.

(10) Number of days of current meteorological data to be entered (7).

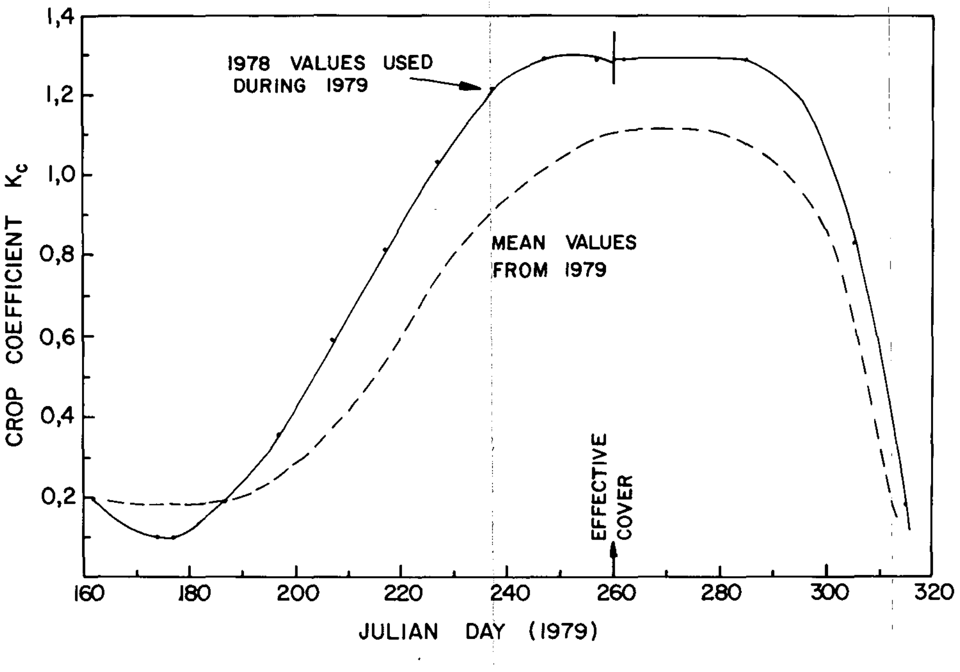

Figure 1
Values of the crop coefficient K_c determined during 1978 and used in the irrigation scheduling model to forecast irrigations during 1979. The estimate of K_c made from measurements during 1979 is also shown.

Input data every seven days

(1) Julian date on which daily meteorological data begins.

(2) Ten days of daily meteorological data which includes the last three days of the previous week and the seven days of the current week. Maximum and minimum air temperature, rainfall, wind run, solar radiation and minimum relative humidity are needed.

(3) Dates of irrigations during the meteorological data period and the amounts applied to each field.

(4) Julian date of last irrigation and total rainfall since the last irrigation on each field.

(5) The level of soil water depletion on the beginning day. The value can be either a field measurement or the predicted depletion from the previous week. For purposes of testing the accuracy of the model predictions during 1979 the measured value of soil water depletion on Julian day 205 (39 days after sowing) was used as input.

Thereafter the value of the soil water depletion used at the start of each week was that which was predicted by the model for the previous week.

(6) Allowed depletion level during the forecast period. For the present experiment a linear function beginning seven days after sowing and reaching a value of 115 mm, 98 days after sowing was used. The function was derived by assuming a downward root growth rate of 13 mm per day (Walter and Barley, 1974) and allowing 50% of the plant available water in the root zone to be depleted (Meyer and Green, 1980b).

Total plant available water in the field was assessed to be 230 mm (Meyer and Green, 1980a) so that once the downward growth of roots had ceased (at about the time of heading, Julian day 264) an allowed depletion of 115 mm could be permitted between irrigations.

Field experiment

The agronomy of the 1979 crop was similar to the previous year (Meyer and Green, 1980a). Briefly, wheat (variety SST 3) was sown on the experimental site at Roodeplaat on 15 June (Julian day 166). The area had received recommended amounts of N, P, and K fertilizer. Rows were 220 mm apart. The field stand which was established was generally poor because of residual herbicide effects but there were several strips of well established, healthy plants over which the treatments were located.

Treatments

A microjet irrigation system (as previously described, Meyer and Green, 1980a) was provided for each of four plots (12 m x 12 m) which were irrigated according to the predictions of the scheduling model. These plots are referred to as S1, S2, S3 and S4. Three soil samples to a depth of 2 m were taken regularly to determine the water content of each plot. Water applications were monitored through a system of rain gauge measurements and water meters.

In addition to the scheduled plots the whole area surrounding the plots was irrigated according to the scheduling model by means of an overhead sprinkler system. Thus the smaller microjet plots were surrounded by a well watered crop. Samples taken from this area were designated DL 1 and DL 2.

A third set of three treatment plots provided with microjet systems received irrigations which were scheduled according to the depletion measured with a weighing lysimeter. The criterion for scheduling was to allow only 50% depletion of the plant available water in the root zone of the lysimeter. Thus maximum depletion allowed between irrigations was 75 mm since total plant available water was found to be 150 mm (Meyer and Green, 1980b). These three plots are referred to as WW1, WW2 and WW3 to indicate that they were well watered throughout the season. Plot WW1 surrounded the lysimeter called L3.

Estimates of grain yield and its components were made by harvesting all plants along 3 m in each of five rows in each field plot and all plants on the 4 m^2 lysimeter surface. Numbers of plants, tillers, heads, spikelets and grains were counted in each sample. Total grain mass and individual grain mass were determined from the cleaned sample. The mean values of the five subsamples was used as the treatment mean.

Results and Discussion

Model output

A typical weekly output from the model is shown in Table 1. The length of the forecast period (14 days in this case) is twice the number of days of current meteorological data which are used. The model is able to deal with meteorological data from many regions with a number of farms and fields in each. Two irrigation dates are forecast. The earlier date assumes no rainfall during the forecast period, while the probability of rainfall for the region is taken into account in the second forecast date. If the probability of rainfall at any time during the season is high the user may decide to delay an irrigation until the second date given on the scheduling printout.

Water Use

The soil water balance as predicted by the scheduling model is shown in Fig. 2. The close correspondence between the predicted level of soil water depletion and the measured values of depletion indicates that the model was predicting the soil water balance fairly accurately.

Because of soil crusting problems on the experimental site which had previously resulted in poor crop establishment irrigations were given as was thought necessary up to Julian day 210. It was originally estimated that the soil water depletion on the day of sowing was 20 mm. Using this depletion level and the irrigations applied to ensure good establishment no irrigations were forecast by the model. After determining the soil water status by sampling on Julian day 205 an irrigation originally scheduled for Julian day 215 was brought forward to Julian day 211 by the following week's forecast. After the irrigation on day 211 the profile was completely filled. Thereafter predicted and measured soil water depletion are in good agreement.

The initial lack of alignment between the model and the field situation illustrates a strength and a weakness in the model. The strength of the model lies in its flexibility since an individual user can proceed with a practice which, experience has shown necessary for say, successful establishment on problem soils. Although the assumed soil water depletion of 20 mm on the day of sowing was too small for the whole soil profile it was

TABLE 1
INFORMATION GIVEN BY THE MODEL USING METEOROLOGICAL DATA FOR THE PERIOD 1 OCTOBER TO 7 OCTOBER 1979

REGION: NORTHERN TRANSVAAL   FORECAST PERIOD: 8 OCT (281) TO 22 OCT (295)
FARM: ROODEPLAAT AGROHYDROLOGY

Region Farm Fld	Crop	Crop coef	Soil water depletion To date mm	 Allowed at irrig	Potential ET mm/day	Last irrigation Date Jday	Next irrigation No rain Date Jday	 With rain Date Jday	Irrigation amount mm
1 1 1	Wheat	1,25	14,53	115,00	10,02	5 Oct (278)	18 Oct (297)	22 Oct (295)	135,3

FORECAST: Fine and mild to hot with possible thundery periods.
Probable rain next 14 days: 3,0 mm/day

DAILY MET. DATA   BEGINNING DATE 1 OCTOBER FOR 7 DAYS

Julian day	Mean temp. °C	Solar radtn. MJ/m^2	Win run km/d	Sat. vapour press Mean kPa	 Dewpt. kPa	Net radtn. MJ/m^2	Soil heat transfer	Rain and irrig.	Potential ET mm/d
274	22,6	20,5	252	3,26	0,62	11,1	0,50	0,4	10,44
275	21,6	17,9	137	3,02	0,61	9,9	−0,19	0,0	7,29
276	23,6	20,3	331	3,31	1,05	11,7	0,38	0,6	10,89
277	22,1	23,5	178	3,00	1,12	13,6	−0,19	0,0	8,01
278	21,7	24,2	228	3,09	0,87	13,5	−0,28	122,4	9,79
279	19,7	11,5	194	2,33	1,50	7,5	−1,06	0,9	4,46
280	20,0	26,0	190	2,61	1,23	15,2	−0,45	0,0	7,72

FORECAST POTENTIAL ET NEXT 14 DAYS: 8,04 mm/d
DRAINAGE: 0,00 mm

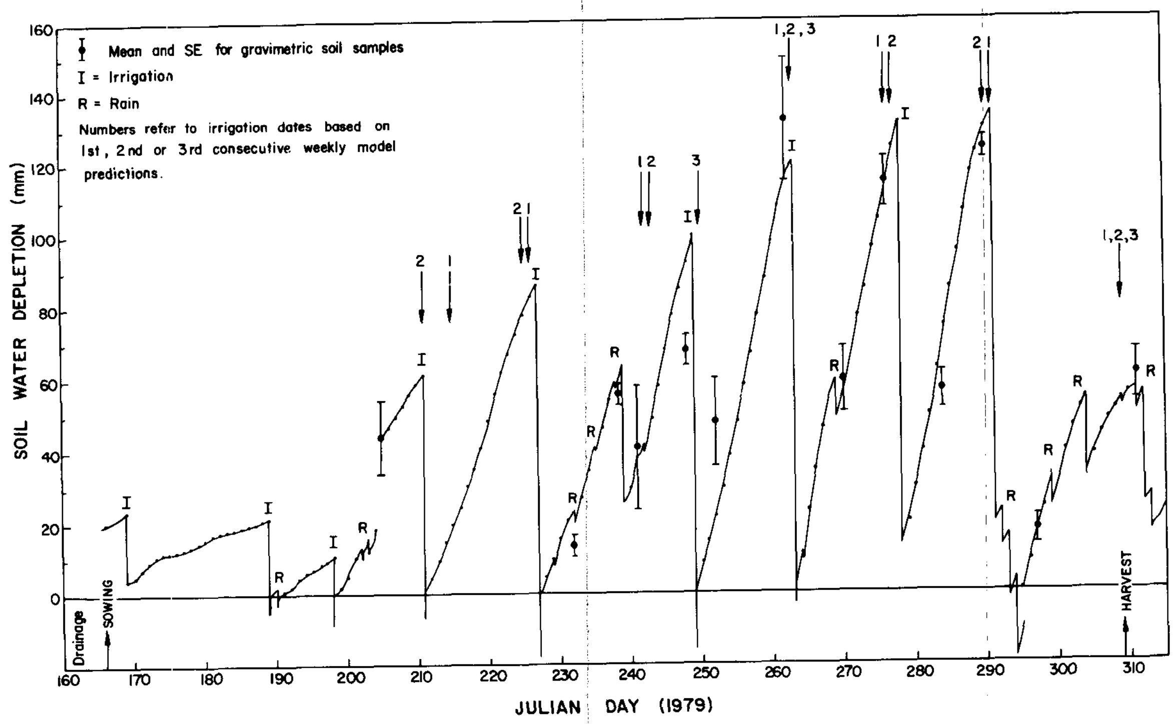

Figure 2
Changes in the soil water balance during the season as predicted by the irrigation scheduling model.

acceptable for the top layers of the profile which were important for germination. The use of soil water depletion from the root zone only rather than from the whole soil profile during initial growth of the crop would be an improvement.

The effect of rain on the forecast date of irrigation is illustrated for Julian days 230 to 250. The first and second predictions scheduled an irrigation on days 242 and 243. However substantial rain on day 239 pushed the irrigation date forward to day 250. The agreement between the forecast irrigation dates obtained from three consecutive weekly predictions of the model on Julian day 263 shows that the expected average evapotranspiration was a good estimate of ET calculated from daily meteorological data and the K_c value.

The apparent drainage after irrigation on Julian days 211, 227 and 249 was caused by applying the recommended amount which had been adjusted above the actual deficit by assuming an efficiency of irrigation of 85%. In this well controlled experiment however the efficiency of irrigation was nearly 100% since the amount applied was measured just above the soil surface or crop canopy with rain gauges.

The treatment of drainage in the original model is not accurate because all water in excess of the maximum plant available water in the profile is assumed to drain. Ideally, functions describing field drainage over time are needed for each soil.

In the original version of the model the soil water deficit after a day of irrigation was assumed to be zero. This would be true if the recommended irrigation amount was given on the recommended date. However irrigations which are less than the total deficit can be given as happened on Julian day 278. The model has been amended so that deficient irrigations are treated in the same way as rainfall. It was also found (Meyer and Green, 1979) that ET on the day of irrigation needed to be included in the water balance to account for measured rates of ET. This is particularly the case when irrigations take only a few hours of a day to complete.

The comparison of the total water balance of the scheduled treatments and the well watered lysimeter L3 is given in Table 2. Total water received by the scheduled plots was higher than on L3 principally because of the higher predicted rates of ET compared with the measured rates. In turn, the higher predicted rates of ET were the result of using a crop coefficient K_c value which was higher than the one determined from measurements during 1979. The lower value of K_c determined for 1979 (Fig. 1) is probably the result of a lower plant population and smaller advection effects when compared to 1978. Advection effects were likely to be smaller in 1979 because the lysimeter was surrounded with a well watered crop as opposed to the dryland area of 1978. Future values of K_c will be adjusted as more data from different seasons are collected.

Since the model appears to have overestimated ET the close agreement between the predicted soil water balance and measured soil water status (Fig. 2) is somewhat surprising. However, results from a model of water flow in the Roodeplaat soil profile (J. Hutson, 1980) indicate that the amount of drainage may have been greater than was predicted. This again emphasises the need for more accurate functions to describe drainage from irrigated soil profiles.

The average time between irrigations (in the absence of effective rainfall) was 12 days for the scheduled plots and eight days for L3 owing to the difference in the maximum allowed depletion levels. The use of 50% depletion of the total plant available water was based on findings from the lysimeter (Meyer and Green, 1980b). However, there is a need to establish that the same deficit levels in the field and lysimeter have the same effect on plant performance. There were no indications from the present experiment that plant performance was affected by allowing a maximum deficit of 115 mm even though this level was approached or exceeded on three occasions.

TABLE 2
TOTAL WATER BALANCE OF THE SCHEDULING TREATMENT PLOTS AND THE WELL WATERED LYSIMETER L3. ALL VALUES ARE IN mm.

	Scheduled	L3
Irrigation (I)	727	443
Rainfall (R)	167	257 (+ run on)
Evapotranspiration (ET)	820	701
Drainage (DR)	67	57
Soil water storage (WS)	+5	− 42
TOTAL AVAILABLE		
I + R − WS	889	742
TOTAL USED		
ET + DR	887	758

Grain yield

The analysis of the components of grain yield and the total grain yield for each of the treatments is given in Table 3. The yields from all comparable treatments apart from DL2 were not significantly different. The reason for the lower yield of DL2, caused principally by fewer heads and smaller grains, was probably due to factors other than water stress. The yield of L3 was determined from all plants on the 4 m^2 lysimeter surface and is not directly comparable with the yields from the field plots. The apparent reason for the higher yield of L3 is the higher number of plants per unit area. It is suggested that under these well watered conditions higher plant populations could be sustained and yields comparable with those from L3 could be obtained under field conditions.

Conclusions

The present field experiment has shown that the "USDA Irrigation Scheduling Model" when properly calibrated for South African conditions can successfully predict a seasonal irrigation program which results in yields not different from well watered treatments. Soil water measurements indicated a fairly good prediction of change in soil water content although adjacent measurements of crop ET with a weighing lysimeter indicated that the model may have overpredicted actual ET by about 15%. Subsequent changes in the crop coefficient K_c should improve the accuracy of prediction. The model was found to be flexible and easily adjusted to account for local effects. Further improvement in the model could be effected by developing general field drainage functions and calculating soil water depletions from the root zone rather than from the total soil profile. It is envisaged that this type of model could include a simple crop growth sub-routine which would further refine the accuracy of predicting crop water requirements.

TABLE 3

COMPONENTS OF THE GRAIN YIELD AND TOTAL GRAIN YIELD. S TREATMENTS WERE IRRIGATED WITH MICROJET SPRINKLERS ACCORDING TO THE SCHEDULING MODEL, WW TREATMENTS WERE IRRIGATED THE SAME AS LYSIMETER L3 AND DL TREATMENTS RECEIVED SCHEDULED IRRIGATIONS WITH OVERHEAD SPRINKLERS

Treatment	No. of plants per m^2	No. of tillers per plant	No. of heads per tiller	No. of spikelets per head	No. of grain per spikelet	Grain mass (mg)	Equivalent yield* (kg/ha)
S1	84,8	5,16	0,97	15,62	2,42	40,1	6434a
S2	77,3	5,14	0,98	15,46	2,51	40,5	6119a
S3	75,8	5,34	0,96	15,52	2,28	38,6	5308a
S4	89,4	4,29	0,95	14,88	2,49	39,8	5373a
WW2	92,4	5,03	0,92	11,95	2,85	41,3	6014a
WW3	93,9	5,10	0,96	14,61	2,60	39,5	6898a
DL1	75,8	4,66	0,97	16,25	2,58	38,3	5502a
DL2	92,4	4,13	0,73	15,93	2,24	34,1	3390b
L3(WW1)	123,5	4,93	0,89	15,52	2,46	35,5	7344

*Mean yields followed by the same letter are not significantly different at P = 0,05 according to Duncan's Multiple Range test.

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References

GREEN, G.C. (1977) *Notes on estimating irrigation requirements of crops in South Africa.* Dept. Agric. Tech. Services, Pretoria, Republic of South Africa. 14 p.

HUTSON, J. (1980) Personal communication.

JENSEN, M.E., ROBB, D.C.N. and FRANZOY, C.E. (1970) Scheduling irrigations using climate-crop-soil data. *J. Irr. Drain. Div., Proc. Am. Soc. Eng.* **96** (IRI) 25 – 38.

JENSEN, M.E., WRIGHT, J.L. and PRATT, B.J. (1971) Estimating soil moisture depletion from climate, crop and soil data. *Trans. Am. Soc. Agric. Eng.* **14** 954 – 959.

MEYER, W.S. and GREEN, G.C. (1979) The prediction of water use by spring wheat in South Africa. *Crop Prod.* **8** 185 – 191.

MEYER, W.S. and GREEN, G.C. (1980a) Leaf growth, phenological development and yield of wheat under different irrigation treatments. *Water S.A.* **6**(1) 21 – 26.

MEYER, W.S. and GREEN, G.C. (1980b) Water use by wheat and plant indicators of available soil water. *Agron. J.* **72** 253 – 257.

PENMAN, H.L. (1963) Vegetation and Hydrology. Tech. Comm. 53, p.124. Commonwealth Bur. of Soils, Harpenden, Herts. England.

STREUTKER, A. (1978) Tensiometer-controlled medium frequency topsoil irrigation: a technique to improve agricultural water management. *Water S.A.* 4(3) 134 – 155.

WALTER, C.J. and BARLEY, K.P. (1974) The depletion of soil water by wheat at low, intermediate and high rates of seeding. *Proc. 10th Int. Congr. Soil Sci. (Moscow)* **1** 150 – 158.