Irrig Sci (1999) 19: 1–6

ORIGINAL PAPER

N. S. Raghuwanshi · W. W. Wallender

Forecasting and optimizing furrow irrigation management decision variables

Received: 9 February 1998

Abstract Furrow irrigation can be better managed if the management decision variables (irrigation time and amount; inflow rate and cutoff) can be determined ahead of time. In this study, these decision variables were forecast and optimized using 1 day ahead grass reference crop evapotranspiration (ET_0) forecasts, based on the ARMA (1,1) time-series model, with a seasonal furrow irrigation model for both homogeneous and heterogeneous infiltration conditions. Heterogeneity in infiltration characteristics was restricted to variations along the furrow length as opposed to variations between furrows. The results obtained were compared with their counterparts using the observed ET_0 for the same period during the 1992 cropping season. Seasonal performance (application efficiency, inflow, runoff and deep percolation volumes) and economic return to water (yield benefits minus seasonal water related and labor costs) were affected by infiltration conditions, while irrigation requirement and bean yield were unchanged. In a given infiltration case, seasonal performance, irrigation schedules, bean yield and economic return to water were comparable (lower than 4% difference) for the two ET_0 conditions. For each ET_0 condition, individual irrigation events resulted in different irrigation designs (inflow rate and cutoff time) except inflow rates with heterogeneous infiltration. Differences in inflow volume were less than 2% and 5%, respectively, for homogeneous infiltration and heterogeneous infiltration. For the conditions studied, furrow irrigation management decision variables can be forecast and optimized to better manage the irrigation system, because irrigation performance was the same for both (forecast and observed) ET_0 cases.

N. S. Raghuwanshi
Agricultural and Food Engineering Dept.,
Indian Institute of Technology,
Kharagpus, WB 721 302, India
e-mail: nsr@agfe.iitkgp.ernet.in

W. W. Wallender (✉)
Department of Hydrologic Science,
Veihmeyer Hall, University of California,
Davis, CA 95616, USA
e-mail: wwwallender@ucdavis.edu
Fax: +1-530-7525262

Introduction

The need to forecast and optimize irrigation decision variables (irrigation schedules, inflow rate and cutoff time) is of paramount importance for better planning and management of irrigation systems. Irrigation requirement is driven by climatic, soil and crop conditions, and can be estimated from the grass reference crop ET (ET_0) at any given time for a specific crop and soil condition using a crop coefficient. Thus, forecast ET_0 can be used to predict the irrigation requirements and irrigation timings for a wide range of soils and crop conditions in a given region at any time during the growing season. Knowing irrigation schedules ahead of time, a farmer can optimize the inflow rate and cutoff time for surface irrigation systems, and the application time for pressurized irrigation systems. Subsequently, the required delivery can be ordered from the irrigation district. A seasonal furrow irrigation model (Raghuwanshi and Wallender 1996) coupled with an economic optimization component can be used to forecast furrow irrigation schedules, inflow rates and cutoff time, employing ET_0 forecasts.

Many irrigation scheduling studies used the long term mean ET_0 values for predicting irrigation schedules without discussing the accuracy of this approach or presenting alternatives (Kincaid and Heermann 1974; Fereres and Snyder 1980; Chesness et al. 1986; Pruitt et al. 1987). Irrigation schedules based on this approach would result in either under- or over-estimation of irrigation requirements because of neglecting year to year variation in ET_0. However, time-series modeling provides an alternative procedure for forecasting ET_0, and it also accounts for temporal variability in ET_0. Gupta and Chauhan (1986) and Marino et al. (1993) used time-series modeling approaches to study the stochastic nature of the weekly irrigation requirement of paddy crop in India, and to forecast monthly ET_0 values, respectively. Monthly ET_0 forecasts are important for estimating seasonal irrigation requirements, but cannot be used for irrigation scheduling because irrigation requirement estimates are needed at short duration (1 or 2 days). Furthermore, optimal irrigation schedules may not fall on weekly or some multiple of weekly intervals. Raghuwanshi and Wallender (1997 a, 1998 b) used a time-series modeling approach to study underlying stochastic mechanisms of neutron probe measured bean crop daily ET and to forecast daily ET_0 values for Davis, California. They found that daily bean crop ET and also ET_0 can be characterized by both the first order autoregressive [AR (1)] and autoregressive moving average [ARMA (1,1)] models. However, for 1 day ahead ET_0 forecasting, the ARMA (1,1) model out-performed the AR (1) model.

Several studies in the literature reported on the optimization of furrow irrigation designs considering either the maximum economic return to water or the minimum irrigation cost (Wu and Liang 1970; Reddy and Clyma 1981; Yitayew et al. 1985; Holzapfel et al. 1986, 1987; Wallender and Rayej 1987; Bautista and Wallender 1993). These studies did not consider irrigation schedules, and assumed that irrigation timing, heterogeneity of the irrigation requirement and seasonal heterogeneity in infiltration characteristics had no effect on irrigation design, crop yield, and economic return to water.

For fixed interval irrigation scheduling and 80% irrigation adequacy at cutoff time, Raghuwanshi and Wallender (1997 b) studied the effects of homogeneous versus heterogeneous soil water balance; soil water properties and rooting depth; and infiltration characteristics on furrow irrigation design, crop yield, and economic return to water. Furrow irrigation designs and economic net return to water were also optimized for variable interval irrigation scheduling criterion (Raghuwanshi and Wallender 1998 a). They assumed that the water available in the furrow at cutoff time was sufficient to achieve irrigation adequacy of 87.5% (Natural Resources Conservation Service recommendation, English and Nuss 1982).

Whittlesey et al. (1986) defined irrigation adequacy as the percentage of the root zone throughout a field which was restored to field capacity during each irrigation. Obtaining an adequacy level of 100% is generally not possible without incurring substantial losses. In order to meet crop water needs, most fields are irrigated to an adequacy level of 75–87.5%. The latter level is commonly sought by U.S. Bureau of Reclamation design criteria (Whittlesey et al. 1986). Irrigation adequacy at cutoff time is defined as the percent of the field receiving the desired amount of water or more, to bring soil moisture deficit to zero at the time of cutoff. Again in this study, 80% irrigation adequacy at cutoff time was considered assuming that water available in the furrow at cutoff time was sufficient to bring irrigation adequacy to 87.5%. It was also assumed that deep percolation was sufficient to leach out salts from the root zone.

The purpose of this paper is to demonstrate the applicability of 1 day ahead daily ET_0 forecasts, using time-series modeling, to predict furrow irrigation management decision variables (irrigation schedules, inflow rate and cutoff time). The results obtained using the ET_0 forecast were compared with those for observed ET_0 condition for the same period (bean crop season, 10 June to 7 September, 1992).

Description of model and input data

The seasonal furrow irrigation model (Raghuwanshi and Wallender 1996) coupled with an economic optimization model was used to simulate the system. The modeling approach is briefly described here and the reader is referred to Raghuwanshi and Wallender (1997 b, 1998 a) for a more detailed description of the model.

Daily water balance was performed using 1 day ahead daily grass reference crop evapotranspiration (ET_0) forecasts as opposed to previous studies in which California Irrigation Management System (CIMIS) estimates of ET_0 were used. The time series modeling methodology for 1 day ahead (lead time of 1 day) ET_0 forecast is given by Raghuwanshi and Wallender (1998 b) and is briefly discussed in this section.

Time series analysis is valid only as long as the past long-term physical conditions are assumed to continue in the future, since the underlying physical variables (temperature, wind, sunshine, radiation) do not appear directly in the analysis. At first this assumption might seem restrictive, but any change in these climatic conditions tends to take place over a period of time, which would most likely be reflected in the historical record and could be factored into a forecasting model before a time-series analysis is performed (Marino et al. 1993). In time-series modeling, it is necessary to remove any periodic component or trend from the series prior to determining a representative stochastic model and computing its coefficients. For ET_0 series, a standardization procedure (Salas et al. 1988) removed the periodic component as follows:

$$z_{\nu,\tau} = \frac{ET_{0_{\nu,\tau}} - \mu_\tau}{\sigma_\tau} \tag{1}$$

where $z_{\nu,\tau}$ is the standardized ET_0; ν is the year; τ is the time interval within the year; and μ_τ and σ_τ are, respectively, the population periodic mean and standard deviation of the ET_0 time series determined from the sample periodic mean and standard deviations estimated using the Fourier series analysis to achieve a standardized ET_0 series.

For standardized ET_0, autocorrelation and partial autocorrelation functions were fitted to determine a representative stochastic model, whereas the appropriate model order was determined using the Akaike Information Criterion (AIC) and the Bayesian Information Criteria (BIC). Based on these analyses, the ARMA (1,1) model was found as a representative model for the standardized ET_0 series:

$$z_t = \phi_1 \, z_{t-1} + a_t - \theta_1 \, a_{t-1} \tag{2}$$

where z_t and z_{t-1} are the standardized observations of time series at time t and $t-1$, respectively; ϕ_1 and θ_1 are the autoregressive (AR) and moving average (MA) coefficients at lag one and were 0.607 and 0.171, respectively (Raghuwanshi and Wallender 1998 b); and a_t is an independently distributed error term with a zero mean and equal variance for all t.

The method of least squares was employed to obtain the model's parameters using International Mathematical and Statistical Library (IMSL) sub-routine NLSE. Furthermore, the IMSL sub-routine NSBJF gave the 1 day ahead (lead time, $L = 1$ day) standardized ET_0 forecast, and the forecast value was updated once the observation for that day was available. It is a two step process in which first the forecast (actual value is not observed so far) is made from the previous day's updated forecast value and then the forecast value is updated using the actual observation of that day. One day ahead ET_0 forecast values were obtained for the complete season (10 June to 7 September 1992). In order to get the forecast values of ET_0, a reverse standardization was performed as follows:

$$\widehat{\mathrm{ET}}_{0_t}(L) = \hat{z}_t(L)\ \sigma_\tau + \mu_\tau \tag{3}$$

where $\hat{z}_t(L)$ is a forecast from time origin t to a lead time L for an actual observation at any time $t + L$, based on information available up to time t; σ_τ and μ_τ are the standard deviation and mean of daily ET_0 for day τ.

The irrigation requirement was equal to soil moisture depletion because daily water balance was based on a fixed interval irrigation scheduling (many irrigation districts in California deliver water on a fixed interval basis) criterion. The delivery system considered here is constrained by delivery interval, but offers flexibility in both flow rate and delivery time to growers. To replenish depleted soil moisture, a space-step solution based kinematic-wave furrow irrigation model (Wallender and Yokokura 1991) was used to simulate the irrigation event and distribution of infiltrated water along the furrow for the range of inflow rates considering 80% irrigation adequacy at time of cutoff. In this case, irrigation cost is a function of inflow rate and would be more for both high and low inflow rates because of different runoff, deep percolation and applied water volumes. However, there is some intermediate inflow rate which minimizes the irrigation cost in order to meet irrigation adequacy criterion (80% at time of cutoff). A goal is to find that inflow rate which minimizes irrigation cost and satisfies the minimum irrigation adequacy criteria. Raghuwanshi and Wallender (1997 b) used the following objective function that minimizes irrigation cost for a prescribed irrigation adequacy at cutoff time:

$$\text{Minimize } f_\mathrm{c} = \sum_{i=1}^{k} \left(V_{\mathrm{w}_i}\ P_\mathrm{w} + V_{\mathrm{r}_i}\ P_\mathrm{r} + V_{\mathrm{d}_i}\ P_\mathrm{d}\right) \tag{4}$$

subject to:

$$172 \le \text{Day of irrigation} \le 237 \tag{5}$$

In Eq. (4), f_c is the minimum seasonal irrigation cost; V_w, V_r and V_d are the total applied water, runoff and deep percolation volumes in $\mathrm{m}^3\ \mathrm{ha}^{-1}$, respectively; P_w, P_r and P_d are the cost of irrigation water, runoff recovery, and deep percolation disposal, and are 0.02, 0.10, and 0.20 $\$\ \mathrm{m}^{-3}$, respectively (Ito 1993); i is irrigation number; and k is the total number of irrigations during the season. Unit runoff and drainage cost values are related to an environmental penalty. In addition, Eq. (4) is also subject to minimum and maximum inflow rate, 80% irrigation adequacy at cutoff time, a chosen irrigation interval (one of 10, 12, 14, 18, or 21 days) and other input variables in the soil moisture and kinematic-wave furrow irrigation models.

The economic return to water can be estimated as follows:

$$\mathrm{NR} = Y\ P_\mathrm{c} - f_\mathrm{c} - \sum_{i=1}^{k} L_{\mathrm{c}_i} \tag{6}$$

and

$$Y_\mathrm{j} = Y_\mathrm{m} \left\{ 1.27 \left(\frac{\sum_{i=1}^{90} \mathrm{ET}_{i,\,j}}{\mathrm{ET}_\mathrm{m}} \right) - 0.27 \right\} \tag{7a}$$

$$Y = \sum_{j=1}^{27} \left[Y_j\ \Delta x\ F_\mathrm{w} \right] N_\mathrm{f} \tag{7b}$$

where Y is the estimated bean yield in $\mathrm{kg\ ha}^{-1}$; P_c is the crop selling price and is 0.57 $\$\ \mathrm{kg}^{-1}$ (Solano County Department of Agriculture 1992); L_c is the irrigation labor cost and is 6 $\$\ \mathrm{ha}^{-1}$ per irrigation (Lamacq 1992); ET and ET_m are the actual and maximum evapotranspiration in cm; and Y_m is the maximum crop (bean) yield in $\mathrm{kg\ m}^{-2}$. The maximum ET (ET_m) and the maximum bean yield (Y_m) are, respectively, 41.6 cm and 0.4196 $\mathrm{kg\ m}^{-2}$ (Tosso 1978). The spatial interval is Δx in m and is equal to 10 m except for the upstream and downstream ends (5 m); F_w is the furrow spacing and is 0.8 m; N_f is the number of furrows/ha; number of days in cropping season = 90 (day 162 to day 251) and number of water balance locations = 27.

In Eq. (4) it was assumed that except water costs, other crop production and irrigation costs did not vary with the inputs and decision variables and thus did not influence the optimum solution. Furthermore, in Eq. (6), the labor cost was based on per unit area and did not vary with the cutoff time. Equations (4) and (6) were solved using a systematic simulation (described below for a given irrigation interval and 80% adequacy at cutoff time) as opposed to a programmed non-linear optimization technique.

Irrigation requirements estimated at 10-m intervals along a 260-m-long furrow using the soil water balance model were passed to the furrow irrigation hydraulic model. Recall that the goal was to find an inflow rate which minimizes irrigation cost and satisfies the minimum irrigation adequacy criteria. Therefore, irrigation events were simulated using a range of inflow rates between the minimum required to advance to the end, 0.5 $\mathrm{l\ s}^{-1}$, and the maximum non erosive flow rate 2.5 $\mathrm{l\ s}^{-1}$, with an increment of 0.1 $\mathrm{l\ s}^{-1}$. Each inflow rate resulted in unique irrigation cost related to runoff, deep percolation, and total inflow. For a given irrigation event, the minimum irrigation cost design was the optimal design and the corresponding water distribution profile along the furrow was passed to the soil moisture model, which then estimated the irrigation depth for the next irrigation event. The above procedure was repeated for all irrigation events between day 172 and day 237. At the end of the season, yield and economic return to water were estimated using Eqs. (7 a, b) and (6), respec-

Table 1 Descriptive statistics for the daily forecast, observed and historical ET_0 series

Statistics	ET_0			
	Forecast[a]	Observed[b]	Historical[c]	Residual[d]
Mean (mm)	6.6	6.5	6.9	0.1
Std. dev. (mm)	0.8	1.0	1.2	0.3
Minimum (mm)	3.5	2.1	1.3	−0.5
Maximum (mm)	8.1	8.2	12.5	1.3
Sum (mm)	590.7	580.1		9.7

[a] Forecast ET_0 for the period of 10 June to 7 September 1992
[b] CIMIS estimates of ET_0 for the period of 10 June to 7 September 1992
[c] CIMIS estimates of ET_0 for the period of 10 June to 7 September, from 1983 to 1991
[d] Residual = daily forecast ET_0 − daily observed ET_0

Table 2 Bean yield and economic return to water for the chosen ET_0 and infiltration conditions

Irrigation interval (days)	Forecast ET_0		Observed ET_0		Difference	
	Bean[a] yield (kg ha^{-1})	Return to water (\$ ha^{-1})	Bean[b] yield (kg ha^{-1})	Return to water (\$ ha^{-1})	Bean yield (%)	Return to water (%)
Homogeneous infiltration						
10	4117	1756	4087	1735	0.7	1.2
12	4021	1742	3989	1728	0.8	0.8
14	3905	1727	3875	1713	0.8	0.8
18	3682	1637	3656	1623	0.7	0.9
21	3425	1609	3403	1600	0.6	0.6
Heterogeneous infiltration						
10	4117	1610	4085	1595	0.8	0.9
12	4017	1527	3987	1510	0.8	1.1
14	3901	1459	3872	1440	0.7	1.3
18	3683	1377	3655	1355	0.8	1.6
21	3420	1431	3398	1419	0.6	0.8

[a] Bean yield modeled using forecast ET_0 values
[b] Bean yield modeled using observed ET_0 values

tively. This procedure was repeated for irrigation intervals of 10, 12, 14, 18 and 21 days.

Daily grass reference crop ET (ET_0) data, from the 1983 through 1992 growing seasons (10 June to 7 September) were obtained from CIMIS for Davis. The first 9 years of data (1983–1991) were used to develop a time-series model, which was then used to forecast ET_0 for the 1992 season. CIMIS ET_0 data for the 1992 season are referred to as observed ET_0. Homogeneous (same infiltration function along the furrow for all irrigation events) and heterogeneous (varied along the furrow and with irrigation event) infiltration functions along with the other input parameters used in the kinematic-wave irrigation and soil water balance models are given by Raghuwanshi and Wallender (1997b).

Results and discussion

A summary of the descriptive statistics for the ARMA (1,1) model forecast ET_0 (10 June to 7 September 1992), the observed ET_0 (10 June to 7 September 1992), the historical ET_0 (10 June to 7 September from 1983 to 1991) and the residual ET_0 series, is presented in Table 1. The residual ET_0 series was obtained by subtracting daily observed ET_0 from daily forecast ET_0. Both ET_0 series gave similar mean daily values, but the standard deviation was the lowest in the case of forecast ET_0. This low variation was also exhibited in minimum and maximum values for the forecast ET_0. Seasonal ET_0 (sum) for the forecast ET_0 was 10 mm higher than that of the observed ET_0. Furthermore, on an average the daily forecast ET_0 values were 0.1 mm greater than the daily observed ET_0.

In all cases, bean yield decreased with the increasing irrigation interval (Table 2) due to a decrease in ET. This declining-yield trend was a result of increased plant water stress, which occurred as actual ET fell below the potential ET and became soil moisture dependent below the field capacity. For a given ET_0 and irrigation interval case, both homogeneous and heterogeneous infiltration conditions resulted in similar yields. Mean seasonal ET was insensitive to variations in infiltration, because irrigation adequacy was the same. However, in all cases, bean yields were slightly higher for forecast ET_0, due to a slightly higher seasonal ET_0 value than the observed ET_0. The difference in bean yield estimated using forecast ET_0 was less than 1% (Table 2).

Economic return to water also followed a declining trend with increasing irrigation interval. Revenue decreased more than the seasonal irrigation cost decreased. Although bean yield was insensitive to infiltration conditions for a given ET_0 and irrigation interval case, economic return to water was lower in the case of heterogeneous infiltration compared to homogeneous infiltration. The decreased economic return to water for heterogeneous infiltration was caused by increased irrigation costs in meeting the same irrigation adequacy criteria. In all cases, economic return to water for forecast ET_0 was slightly higher than for observed ET_0, but the difference was under 2% (Table 2).

To further investigate the applicability of forecast ET_0 in furrow irrigation management, seasonal performance corresponding to the highest net economic return to water (10-day irrigation interval) for both ET_0 conditions was compared (Table 3). An irrigation interval of 10 days resulted in seven irrigation events during the cropping season. The seasonal irrigation requirement was independent of infiltration characteristics, and was similar for both ET_0 conditions (less than 2% difference, Table 3).

For a given ET_0 case, seasonal inflow, runoff, and deep percolation volumes were higher in the case of heterogeneous infiltration compared to homogeneous infiltration (Table 3). In fact, to achieve the same level of irrigation adequacy in heterogeneous infiltration conditions, more water was needed, which also resulted in greater losses (runoff + deep percolation, Table 3). Seasonal inflow, runoff and deep percolation volumes were similar (difference

Table 3 Seasonal performance for a 10-day irrigation interval under the chosen ET_0 and infiltration conditions

Seasonal performance	Homogeneous infiltration			Heterogeneous infiltration		
	Forecast ET_0	Observed ET_0	Difference (%)	Forecast ET_0	Observed ET_0	Difference (%)
Irrigation interval (days)	10	10	0.0	10	10	0.0
Number or irrigations	7	7	0.0	7	7	0.0
Irrigation requirement (cm)	34.3	33.9	1.2	34.3	34	0.9
Inflow ($m^3\ ha^{-1}$)	5896	5890	0.1	6808	6770	0.6
Runoff ($m^3\ ha^{-1}$)	709	736	–3.7	1254	1245	0.7
Deep percolation ($m^3\ ha^{-1}$)	1801	1798	0.2	2165	2165	0.0
Application efficiency (%)	56.4	55.7	1.3	49.8	49.5	0.6

Table 4 Individual irrigation schedules and designs for a 10-day irrigation interval under the chosen ET_0 and infiltration conditions

Day of irrigation	Forecast ET_0			Observed ET_0			Difference			
	Irr. req. (cm)	Inflow rate ($l\ s^{-1}$)	Cutoff time (min)	Irr. req. (cm)	Inflow rate ($l\ s^{-1}$)	Cutoff time (min)	Irr. req. (%)	Inflow rate (%)	Cutoff time (%)	Inflow volume (%)
Homogeneous infiltration										
172	1.9	1.0	154	1.8	1.1	141	5.6	–9.1	9.2	–0.7
182	3.2	0.7	288	3.1	0.8	247	3.2	–12.5	16.6	1.9
192	4.5	0.6	431	4.3	0.7	363	4.7	–14.3	18.7	1.6
202	5.8	0.6	539	5.8	0.6	545	0.0	0.0	–1.1	–1.1
212	6.4	0.6	591	6.5	0.6	600	–1.5	0.0	–1.5	–1.5
222	6.4	0.5	692	6.4	0.5	689	0.0	0.0	0.4	0.4
232	6.1	1.2	344	6.1	1.1	373	0.0	9.1	–7.8	0.6
Heterogeneous infiltration										
172	1.9	0.7	235	1.8	0.7	226	5.6	0.0	4.0	4.0
182	3.2	0.6	365	3.1	0.6	353	3.2	0.0	3.4	3.4
192	4.5	0.6	467	4.3	0.6	452	4.7	0.0	3.3	3.3
202	5.8	0.5	680	5.8	0.5	683	0.0	0.0	–0.4	–0.4
212	6.4	0.7	700	6.5	0.7	709	–1.5	0.0	–1.3	–1.3
222	6.4	0.7	706	6.4	0.7	703	0.0	0.0	0.4	0.4
232	6.1	1.1	342	6.1	1.1	345	0.0	0.0	–0.9	

Irr. req. Irrigation requirement

of less than 1%, Table 3) for both ET_0 conditions, except for runoff in the case of forecast ET_0 and homogeneous infiltration (4% difference). In this particular case, higher runoff was caused by variation in individual irrigation designs (inflow rate and cutoff time, Table 4).

Use of higher seasonal inflow volume to satisfy the same seasonal irrigation requirement resulted in lower average application efficiency in the instances where heterogeneous infiltration was used rather than homogeneous infiltration. In a given infiltration instance, application efficiency was insensitive to ET_0 (less than 2% difference, Table 3). Seasonal application efficiency values (Table 3) corresponded to nearly full irrigation because the seasonal deficit area was 5% and 8% for homogeneous and heterogeneous infiltration conditions, respectively. Thus, the seasonal irrigation adequacy was above 90%. These application efficiency values are also comparable with the earlier findings of Whittlesey et al. (1986). They reported representative application efficiency for a bean crop under different levels of furrow irrigation management as 37.5%, 42.5%, 52.5%, 57%, and 57.5% for existing farmers' practice, furrow irrigation with irrigation scheduling, cutback irrigation system, pump-back furrow irrigation system, and gated pipe furrow irrigation system, respectively. To obtain both high application efficiency and maximum economic return to water, a certain level of deficit irrigation occurs. The deficit irrigation case is beyond the scope of the present study.

Seasonal performance (Table 3) is an indicator of overall irrigation practices during the season but the same seasonal performance can be achieved with different irrigation schedules and designs (Table 4). Individual irrigation schedules are not the same for the two ET_0 cases. Irrigation requirement increased up to the fifth irrigation event, and thereafter declined slightly as the crop approached maturity. Early in the season, irrigation requirements were greater for forecast ET_0 compared to observed ET_0 because forecast ET_0 values were higher than the observed ET_0 values. The higher variability in historical series at the beginning of the cropping season gave higher forecast ET_0 values since these are related to historical mean and standard deviation (Eq. 3). The difference in irrigation requirement ranged from 0 to 6%. As for the seasonal irrigation requirement, individual irrigation requirements were similar for homogeneous and heterogeneous infiltration characteristics.

For homogeneous infiltration characteristics, inflow rates and cutoff times varied between ET_0 conditions. However, lower inflow rates were compensated by longer cutoff times resulting in less than 2% differences in inflow volumes for forecast ET_0 compared to observed ET_0 early in the season, but the reverse occurred later (Table 4). In the case of heterogeneous infiltration, inflow rates were similar and differences in cutoff times and inflow volumes were less than 5% (Table 4). Using the historical mean ET_0 values, differences in inflow volume for individual irrigation events were less than 12% (Raghuwanshi and Wallender 1997b).

For both infiltration conditions, furrow inflow rate and cutoff time varied with irrigation requirement (Table 4). Also, irrigation designs (inflow rate and cutoff time) were sensitive to infiltration conditions. For the same irrigation requirement, optimum flow rates were lower and cutoff times were longer for heterogeneous infiltration than homogeneous infiltration, which resulted in higher inflow volumes for heterogeneous infiltration. Thus, forecast ET_0 can be used for managing furrow irrigation systems for both homogeneous and heterogeneous infiltration conditions, if infiltration information is available. For practical purposes, infiltration measurements can be taken a day before the irrigation event, since the day of irrigation is fixed.

Summary and conclusions

One day ahead ET_0 forecasts based on the ARMA(1,1) time-series model were used to predict both irrigation schedules and optimum furrow irrigation designs (inflow rate and cutoff time), for both homogeneous and heterogeneous infiltration conditions. The results were compared with those obtained using the observed ET_0 for the 1992 bean crop season.

Bean yield and economic return to water as well as seasonal irrigation requirement, application efficiency, inflow, runoff, and deep percolation for the optimal 10-day irrigation interval were nearly the same for observed and forecast ET_0. Irrigation designs were similar for observed and forecast ET_0 except early in the season when flow rates were slightly lower and cutoff times were higher for forecast ET_0. Although bean yield was similar, economic return to water as well as seasonal irrigation performance was lower for heterogeneous infiltration compared with homogeneous infiltration. Cutoff times were longer and inflow rates were lower for heterogeneous soils compared to homogeneous soils.

In summary, irrigation performance was the same for both forecast and observed ET_0. This suggests that furrow irrigation management decision variables can be forecast and optimized for the conditions studied. However, similar studies need to be carried out considering more years of data to evaluate the adaptability of the methodology presented in this paper.

References

Bautista E, Wallender WW (1993) Optimal management strategies for cutback furrow irrigation. J Irrig Drain Div ASCE 119: 1099–1114

Chesness JL, Cochran CL, Hook JE (1986) Predicting seasonal irrigation water requirements on coarse-textured soils. Trans ASAE 29: 1054–1057

English MJ, Nuss GS (1982) Designing for deficit irrigation. J Irrig Drain Div ASCE 108: 91–106

Fereres E, Snyder RL (1980) Computerized irrigation scheduling. University of California Soil and Water Report No. 45

Gupta RK, Chauhan HS (1986) Stochastic modeling of irrigation requirements. J Irrig Drain Div ASCE 112: 65–76

Holzapfel EA, Marino MA, Morales JC (1986) Surface irrigation optimization models. J Irrig Drain Div ASCE 112: 1–19

Holzapfel EA, Marino MA, Morales JC (1987) Surface irrigation nonlinear optimization models. J Irrig Drain Div ASCE 113: 379–392

Ito H (1993) Furrow irrigation optimization with non uniform soil and optimal number of samples. M.S. Thesis, University of California, Davis

Kincaid DC, Heermann DF (1974) Scheduling with programmable calculator. ARS-NC-12. Agricultural Research Service

Lamacq S (1992) Farm water use efficiency related to irrigation scheduling and water delivery flexibility. M.S. Thesis, University of California, Davis

Marino MA, Tracy JC, Taghavi SA (1993) Forecasting of reference crop evapotranspiration. Agric Water Manage 24: 163–187

Pruitt WO, Fereres E, Kaita K, Snyder RL (1987) Reference evapotranspiration (ET_0) for California. Bull. 1922, University of California Agricultural Experiment Station, Davis

Raghuwanshi NS, Wallender WW (1996) Modeling seasonal furrow irrigation. J Irrig Drain Div ASCE 122: 235–242

Raghuwanshi NS, Wallender WW (1997a) Field measured evapotranspiration as a stochastic process. Agric Water Manage 32: 111–129

Raghuwanshi NS, Wallender WW (1997b) Economic optimization of furrow irrigation. J Irrig Drain Div ASCE 123: 377–385

Raghuwanshi NS, Wallender WW (1998a) Optimization of furrow irrigation schedules, designs and net return to water. Agric Water Manage 35: 209–226

Raghuwanshi NS, Wallender WW (1998b) Forecasting daily grass reference crop evapotranspiration. Int Agric Engin (submitted)

Reddy M, Clyma W (1981) Optimal design of furrow irrigation system. Trans ASAE 24: 617–623

Salas JD, Delleur JW, Yevjevich V, Lane WL (1988) Applied modeling of hydrologic time series. Water Resources Publications Littleton, Colo.

Solano County Department of Agriculture (1992) Agricultural crop report. Fairfield, Calif.

Tosso JE (1978) Effects of different levels of applied water on the vegetative growth, yield and water production function in dry beans (*Phaseolus vulgaris L*). Ph.D. dissertation, University of California, Davis

Wallender WW, Rayej M (1987) Economic optimization of furrow irrigation with uniform and nonuniform soil. Trans ASAE 30: 1425–1429

Wallender WW, Yokokura J (1991) Space solution of kinematic-wave model by time iteration. J Irrig Drain Div ASCE 117: 140–144

Whittlesey NK, McNeal BL, Obersinner VF (1986) Concepts in irrigation management. In: Whittlesey NK (ed) Energy and water management in western irrigated agriculture. Westview Press, Boulder, Colo.

Wu IP, Liang T (1970) Optimal design of furrow length of surface irrigation. J Irrig Drain Div ASCE 96: 319–332

Yitayew M, Letey J, Vaux HJ Jr, Feinerman E (1985) Factors affecting uniformity and optimal water management with furrow irrigation. Irrig Sci 6: 201–210