Development of an Irrigation Scheduling Model

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ABSTRACT

This paper presents an irrigation scheduling software named "Mehran Model" which computes reference ET_o (Evapotranspiration) using FAO-56 Penman Monteith method and crop evapotranspiration (ET_c) by dual crop coefficients. The model can develop irrigation schedules for sixty-six crop types using soil and water balance approach. The model distinguishes soil texture classes, irrigation methods, and designs real time irrigation schedule for a crop using daily weather data of a reference site. The Mehran Model also includes planning on demand basis as well as rotational (warabandi) irrigation schedules, and synchronizes both systems as well. The model has been field tested and validated on planning and management of irrigation schedules for cotton and wheat crops in Lower Indus Basin of Pakistan. Statistical analysis showed that the model at an average overestimated seasonal ET_c of cotton and wheat crop by 2.41% and 4.31% respectively.

Key Words: **Mehran Model, Irrigation Scheduling, Crop Evapotranspiration.**

1. INTRODUCTION

Fresh water use is rapidly increasing due to population growth, industrialization, and living standards. Clothier [1] perceptively stated that we already live in an age dominated by technology, and this trend will proceed apace as we approach the twenty-first century. Scientific research is required for basic understanding to allow technological advances.

Irrigated agriculture is a major consumer of fresh water; therefore, efficient irrigation water utilization based on sound methodology is becoming more important than ever. Simulation models of irrigation system, when coupled with appropriate data source, have a great potential for bringing irrigation research into modern technology. Now computer simulation has become a powerful tool for analyzing the impacts of irrigation practices on the soil-water balance.

SWB (Soil Water Balance) models such as CANEGRO, ACR, APSIM, CANESIM, ZIMsched 2.0, and CROPWAT use soil water budget equation [2-8]. These models can not be used for real-time irrigation scheduling on daily basis.

The reliable simulation of evapotranspiration, water balance and soil water content is obviously one of the crucial points in the application of any SVAT (Soil Vegetation Atmosphere) model. Water balance calculations in SVAT models (including crop models) should therefore be tested prior to application in different sites and environments.

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Most of the models are site and crop specific which require complex input data to design irrigation schedules while some of the models are not single unit; therefore, user needs to transfer data and results from one to other model which is sometimes quite cumbersome. Most professionals involved in irrigation planning and management prefer models which are adequately fitted to their programs. Hence there has been a need for simple and user friendly model which can work with regional irrigation systems.

Mehran model has been developed to design irrigation schedules on demand basis as well as on warabandi system which is fixed rotational irrigation water supplying system. The model is quite flexible regarding data input interface, and data alteration for redesigning the irrigation schedules.

2. MEHRAN MODEL-COMPUTATION EQUATIONS

2.1 Water Balance Approach

Scheduling irrigations using the soil-water balance method is world-wide accepted and practiced by irrigation researchers and professionals. Water balance in the form of depletion (Equation 1) is the major governing equation of the Mehran Model for irrigation scheduling. The model maintains daily soil-water balance spreadsheet, which is computed by the Equation (1):

$$D_{ri} = D_{ri-1} + ET_{ci} + DP_i - \frac{I_i}{f_w} - R_i \quad (1)$$

Where D_{ri} is soil-moisture depletion in the root zone at the end of day_i (mm), $D_{r\ i-1}$ is soil-moisture depletion in root zone at end of day_{i-1} (mm), ET_{ci} is computed crop evapotranspiration since day_{i-1} (mm), DP_i is deep percolation due to gravity since day_{i-1} (mm), I_i is net irrigation depth since day_{i-1}, which infiltrates in the soil (mm), f_w is fraction of soil surface wetted by irrigation or rainfall, and R_i is effective rainfall depth since day_{i-1} that infiltrates in the soil (mm).

When soil-water depletion becomes equal or less than RAW_i, that is the time to irrigate (refill) the soil by an equal amount that depleted in the root zone below soil-moisture at field capacity level.

The FAO-56 modified Penman-Monteith [9]; Equation (2) has been programmed into the Mehran model for computing reference evapotranspiration (ET_o). The Equation is given as:

$$ET_o = \frac{0.408\,\Delta\left[R_n - G\right] + \gamma \frac{900}{T+273} u_2 \left[e_s - e_a\right]}{\Delta + \gamma\left[1 + 0.34\,u_2\right]} \quad (2)$$

Where ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is air temperature at 2m height (°C), u_2 is wind speed at 2m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s-e_a is saturation vapour pressure deficit (kPa), Δ is slope of vapour pressure curve (kPa $°C^{-1}$), and is psychrometric constant (kPa $°C^{-1}$).

2.2 Crop Coefficient and Evapotranspiration

To optimize irrigation scheduling through ET (Evapotranspiration), the first step is to compute an accurate ET_o. The ET_o refers to the rate of ET from a well watered hypothetical grass surface of known characteristics (height and surface resistance). It expresses the ET demand of the atmosphere at a given location irrespective of crop type, stage of development, and management practices. The different mathematical and empirical equations used for ET_o estimation are based on different concepts, and the variables (inputs) to include depend on the equation selected [10].

There are two types of ET_o data that can be used in ET based irrigation scheduling: (1) historical ET_o and (2) real-time ET_o. Historical ET_o represents long-term daily, monthly, or seasonal ET_o averages, for a long record of data that includes yearly and 10-year variations is most representative. Real-time ET_o used to schedule irrigation is updated daily, which provides an advantage over the historical ET_o-based planning because it accounts for daily variations in weather conditions. ET_o and ET_c computed from hourly or daily weather data for model predictions in real time irrigation scheduling [11-13]. Another approach to real-time irrigation scheduling consists of deriving crop coefficients (K_c) by lysimeter to estimate the actual crop evapotranspiration (ET_{ca}) for determining irrigation requirements. Various applications and modeling approaches are being practiced pertaining to the applications for estimation of ET_{ca} at regional or over all irrigation system scales [14-16]

In dual crop coefficients approach, crop coefficient (K_c) is divided into two separate coefficients; basal crop coefficient (K_{cb}) used for crop transpiration demand and evaporation coefficient (K_e) for evaporation computation from upper layer of soil surface.The K_{cb} integrates the characteristics of the crop (e.g. crop height, net radiation absorbed at the land surface, canopy resistance, and evaporation from bare soil surface) into the ET_c estimation, to account for the difference in transpiration between the actual crop and the reference grass. The K_{cb} value changes over the growing period for a crop due to changes in the crop characteristics such as ground cover, crop height and leaf area. Crop growth period is divided into four stages (i.e. initial stage, crop development, mid-season stage, and late season stage) and K_c values are calculated based on these stages. The initial stage is the period between the sowing time and 10% ground cover. The crop development stage refers to the period from 10% ground cover to the initiation of flowering. The mid-season stage accounts to the period between full crop cover and the start of maturity which is indicated by the aging, yellowing, browning of leaves or leaf drop, while the late season stage covers the period between maturity and harvest. Scientifically developed actual crop coefficient (K_{ca}) for crops is based on local management practices, variety and environmental conditions. It is used to generate actual ET (ET_{ca}) for estimating net irrigation water requirement. However, the daily ET_c is computed by the model by the Equation (3):

$$ET_{ci} = (K_{cbi} + K_{ei})\, ET_{oi} \quad (3)$$

where ET_{ci} is daily crop evapotranspiration (mm), K_{cbi} is daily basal crop coefficient, K_{ei} is daily evaporation coefficient. The dual crop coefficients procedure is required to be conducted on daily basis and intended for applications using computer.

The daily root depth (Z_{ri}) is computed by the Equation (4):

$$Z_{ri} = Z_{rmin} + (Z_{rmax} - Z_{rmin}) \frac{K_{cbi} - K_{cbini}}{K_{cbmid} - K_{cbini}} \; for J \leq J_{mid} \quad (4)$$

and Z_{ri} is Z_{rmax} for $J > J_{mid}$

Where Z_{ri} is depth of the root zone on day_i (mm), Z_{rmin} is initial depth of the root zone set prior to sowing (mm), Z_{rmax} is maximum depth of the root zone at mid stage and thereafter (mm), and J is day of a year 1-365 (or 1-366 for a leap year).

TEW (Total Evaporable Water) from topsoil is computed by the Equation (5):

$$TEW = 1000_{FC} - 0.5\theta_{WP})Z_e \quad (5)$$

Where TEW is Total Evaporable Water or maximum depth of water that can be evaporated from the soil when the topsoil has been completely wetted (mm), and Z_e is depth of the surface soil layer that subject to drying by way of evaporation (~0.10m). After TEW, daily REW_i is computed by the cumulative soil-moisture depletion amount on day_i (mm).

The TAW to the crop is computed by the Equation (6):

$$TAW_i = (\theta_{FC} - \theta_{WP})\, Z_{ri} \quad (6)$$

Where TAW_i is Total Available Water in the root zone on day_i (mm), θ_{FC} is moisture content at the field capacity, θ_{WP} is moisture content at wilting point, and Z_{ri} is depth of the root zone on dayi (mm).

The daily RAW in the root zone is computed by the Equation (7):

$$RAW_i = MAD \times TAW_i \quad (7)$$

Where RAW_i is Readily Available Water in the root zone on day_i (mm), and MAD is Management Allowed Depletion in the root zone on day_i (fraction).

3. MEHRAN MODEL

The Mehran Model is comprised of five basic components: (1) the main interface (Fig. 1(a-b)), which directs the execution of the software model with drop-down menus functionality; (2) the new crop data input interface (Fig. 2), for data entry about crop type, crop min and max root depths, soil type, and irrigation method via a user friendly interface; (3) the daily weather input data interface (Fig. 3), temperatures (T_{max} T_{min} T_{dew}), wind speed, daily sunshine hours, latitude and altitude of the site, amount of irrigation applied, amount of effective rainfall occurrence; (4) the daily water balance module (Fig. 4), which computes daily reference and crop evapotranspiration by dual crop coefficients via SWB approach, and (5) irrigation planning module (Fig. 5), plans for on crop water demand system, rotational, and synchronizing on demand and rotational systems. Average monthly weather Tables 1-2 shows temperatures (^{o}C), wind speed (m/s), sunshine hours and rainfall (mm) data for whole year (Fig. 6). This weather data could be input by user or directly loaded by already existing file. The crop data summary form shows all characteristics of the selected crop; and the results are presented by tables, graphs, and printouts.

Mehran Model is simple and easy to run decision support system. The system was particularly developed for irrigation management support to plan and manage irrigation scheduling for general crops. The model was experimentally field tested on two major crops (wheat and cotton) in lower Indus basin of Pakistan.

4. THE MODEL EVALUATION AND VALIDATION

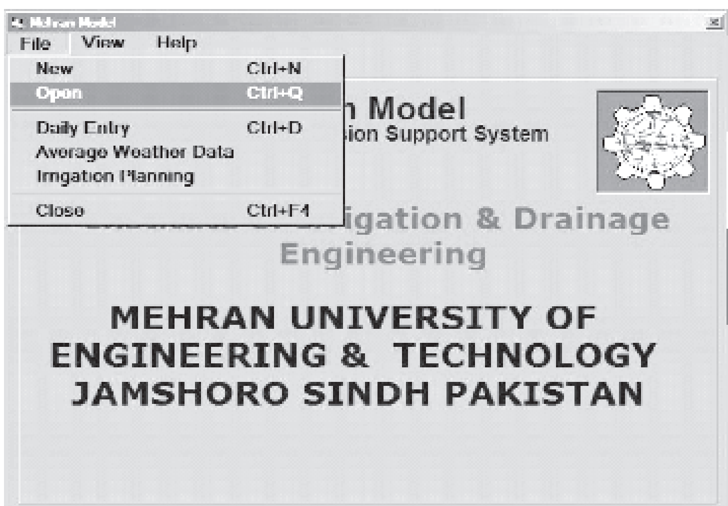


FIG. 1(A). FILE MENU ON MAIN MODULE OF MEHRAN MODEL
FIG. 1(B). VIEW MENU ON MAIN MODULE OF MEHRAN MODEL

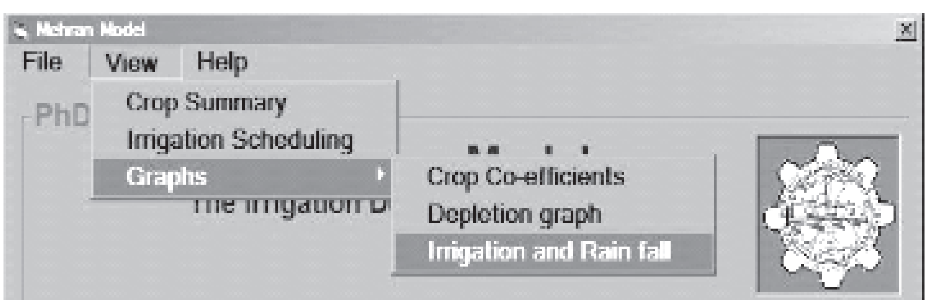


FIG. (2). NEW CROP FILE MODULE

Field experiments at MAD levels of 55, 65 and 75% for cotton crop, and at MAD levels of 45, 55 and 65% for wheat crop were carried out for irrigation scheduling. The daily ET_{ca} was observed through gypsum block readings and a drainage lysimeter. The seasonal ET_{ca} of cotton in the experiments were observed of 486, 413, and 397mm and those computed by the model were 504, 421, and 404mm. Similarly, the observed seasonal wheat ET_{ca} were 363, 359, and 332mm, and those computed were 383, 369, and 355mm [17-19].

Quantitative agreement between actual and computed values is based on the RMSE (Root Mean Square Error), SD (Standard Deviation), ARE% (Average Relative Error Percentage), and coefficient of determination (R^2), which statically gives the ratio between actual to total computed errors. Statistical criteria were applied to evaluate the model performance in computation of ET's using Equations (8-11) and a software Analyse-it.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(A_i - C_i\right)^2}{\sum_{i=1}^{n}\left(A_i - a\right)^2} \tag{8}$$

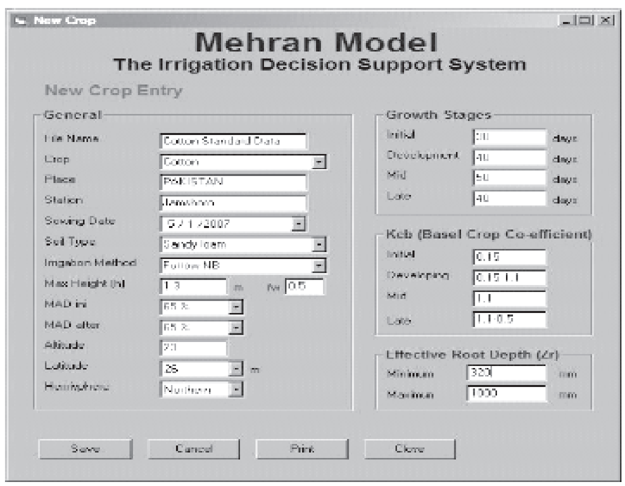


FIG. (3). DAILY ENTRY MODULE

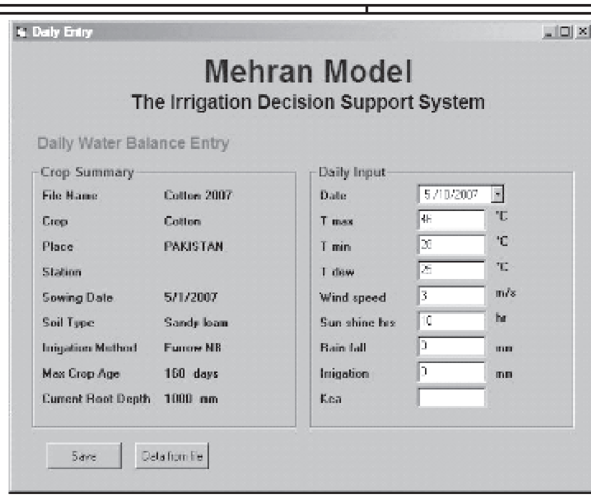


FIG. 4. IRRIGATION SCHEDULING SHEET BY DAILY WATER BALANCE

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(C_i - A_i\right)^2}{n}} \tag{9}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n} \left| \left(A_i - a\right)^2 - \left(C_i - c\right)^2 \right|}{n-1}} \tag{10}$$

$$ARE\,\% = \frac{\sum_{i=1}^{n} \left(C_i - A_i\right)}{n(a)} * 100 \tag{11}$$

Where A_i is the values of ET_{cai} (mm), C_i is the values of ET_{ci} (mm), a is absolute mean of ET_{cai} (mm), c is absolute mean of ET_{ci} (mm), and n is total number of values (in case of cotton n is 160, and for wheat experiments, n is 120).

The F-test compares the variances of two distributions, while the T-test compares their means. The F-test informs precisely how much more of the variation in computed crop ET explained by the actual. A large proportion indicates a significant relation. A paired sample T-test is used to determine whether there was a significant difference between the average values of the same measurement made under two different conditions. In T-test both measurements made on each unit in a sample, and the test based on the paired differences between these two values. The null hypothesis was that the difference in the average values was 0.

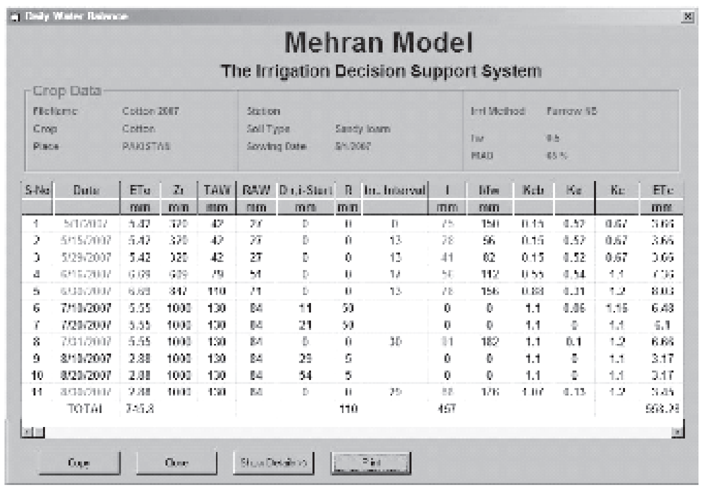
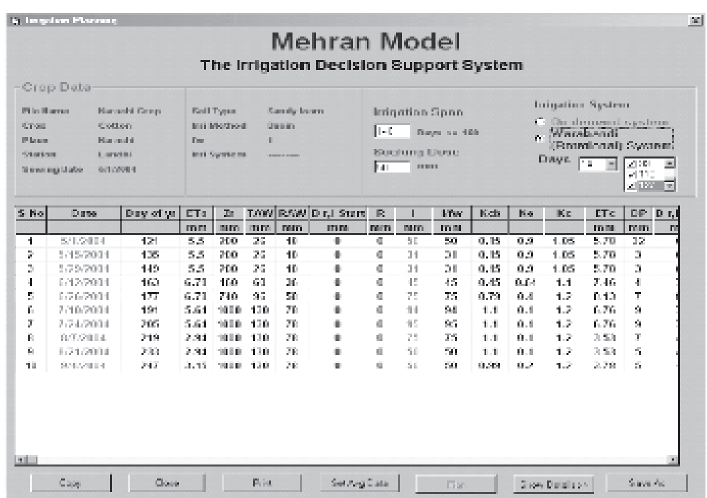


FIG. 5. IRRIGATION PLANNING MODULE OF MEHRAN MODEL

FIG. 6. AVERAGE MONTHLY WEATHER DATA



The result of various statistical parameters for cotton and wheat crops is shown in Tables 1-2.

In most areas of scientific research, the criterion for statistical significance level is conventionally set at the 5% level i.e. the p<=0.05. As in the case of T-test, p=0.04 which is acceptable boundary of significance. The resulted variation due to regression maximum F-test=999 (set p<0.0001, 95% CL (Confidence Level). A strong relationship between actual and computed values of crop ET shows a high value of F-test.

5. CONCLUSIONS

The Mehran model is found flexible and user-friendly irrigation scheduling system. The design potential of the various components of the model provides multiple choices to users for designing irrigation schedules in different irrigation water supply systems. The model's mechanism is capable of designing real time, planning irrigation schedules for generic crops. It works with soil-plant-atmosphere variety which makes good use of a weather, soil, and crop databases. Statistical evaluation of the model shows averagely 92% efficiency which supports its successful use in practice for cotton and wheat crops' irrigation scheduling in Lower Indus Basin of Pakistan.

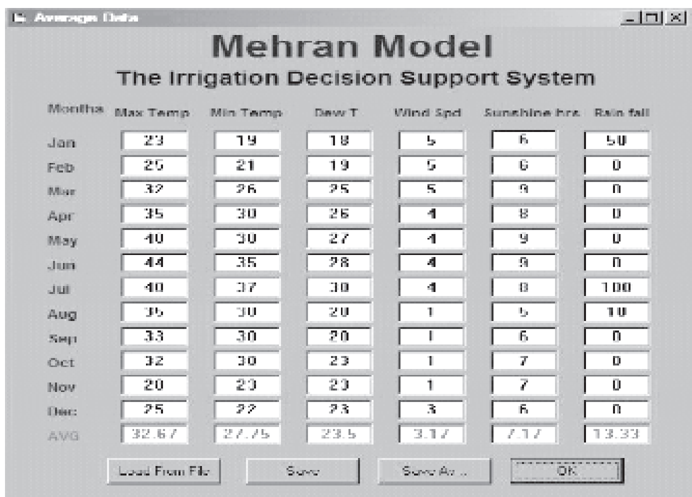


TABLE 1. STATISTICAL COMPARISON BETWEEN THE ACTUAL AND COMPUTED COTTON ET's

Experiment Cotton	R^2	SD (mm)	RMSE (mm)	ARE (%)	T-Test	2-Tailed (P)	F-Test
MAD 55%	0.93	0.28	0.33	3.21	4.77	0.001	3946.00
MAD 65%	0.96	0.55	0.63	2.00	1.16	0.024	550. 57
MAD 75%	0.96	0.53	0.64	2.02	0.15	0.034	507.96
Average	0.95	0.45	0.53	2.41	2.03	0.020	2226.98

TABLE 2. STATISTICAL COMPARISON BETWEEN THE ACTUAL AND COMPUTED WHEAT ET's

Experiment Wheat	R^2	SD (mm)	RMSE (mm)	ARE (%)	T-Test	2-Tailed (P)	F-Test
MAD 45%	0.89	0.47	1.58	4.13	3.90	0.002	644
MAD 55%	0.90	0.44	0.44	2.80	2.09	0.039	999
MAD 65%	0.88	0.50	1.64	6.01	3.80	0.002	562
Average	0.89	0.47	1.22	4.31	3.26	0.014	735

6. RECOMMENDATIONS

The model estimates net irrigation depth in the irrigation scheduling, it is recommended that the depth must be divided by field water application efficiency to change it into gross irrigation depth. The Mehran model does not account water addition from underground by capillary rise and losses as runoff from farm field in the growing season, which may be considered where water table is shallow and method of flood irrigation is in practice. Adoption of advanced technology in irrigated agriculture is the prime need of time to cope with water shortages for present and future food production. It is suggested that freshwater be used efficiently with the help of modern tools in irrigated agriculture.

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