CropIrri: A Decision Support System for Crop Irrigation Management

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Abstract: A field crop irrigation management decision-making system (CropIrri) was developed based on the soil water balance model, crop phenology model, root growth model, crop water production function, and irrigation management model. The irrigation plan is made through predicating of soil water content in root zone and daily crop water requirement using historical and forecasting weather data, measured real time soil moisture data. CropIrri provided four decision modes of non-limiting irrigation, water-saving irrigation, irrigation with experience and user custom irrigation. The main function of CropIrri includes: pre-sowing and real-time irrigation management decision-making support, simulation of soil water dynamics in the root zone, evaluation of the effect of certain irrigation plan on crop yield reduction, and database management. A case study of wheat crop irrigation management by CropIrri showed its practical value and benefit. It could be an objectives-oriented, multi users-oriented and practical irrigation management decision-making tool.

Keywords: Field crop; Irrigation; Decision support; Model

1. INTRODUCTION

Field crop irrigation scheduling is a major part in crop production management, it is important in using of water resources rationally and increasing crop water productivity. In recent years, studies on the establishment of optimal irrigation methods and irrigation decision support system have obtained important achievements (J. A. de Juan, 1996; J.-E.

Bergez et al, 2001; Zhu et al, 2003; Zhu et al, 2005; Zhang et al, 2006). These studies helped to improve crop water management and irrigation decision-making level, but there still exist many problems, such as limited to certain regions, difficult to determine growth period accurately, complex model parameters or large database, and so on.

This paper highlights the following aspects to improve and to overcome the traditional weaknesses of agricultural irrigation systems, then to build the field crop irrigation management decision support system, CropIrri. (1) Using the multi-annual mean meteorological data to make irrigation schedule before sowing, and use the forecast weather data to carry out the real-time irrigation management; (2) Using simulation model for crop phenology to determine the adaptability of different varieties in different regions, and to simulate the length of growth stages, which is important to enhance the accuracy of parameters at different stages; (3) Using root growth model to simulate the root growth and elongation, then system can compute soil water content in the root zone more accurately; (4) Set custom irrigation schedules for senior user, call the crop water production function to evaluate yield losses in different stages for certain irrigation schedule; (5) simplify some input parameters to ensure system running. When input parameters are short, users can select several kinds of parameters provided by system. This can expand its regional serviceability and the farmer’s usability.

2. SYSTEM DESIGN AND PRINCIPLE

Through the analysis of basic relation and quantitative algorithm between soil water deficit and crop water consumption, management decision-making levels and types of crop variety, environmental factors and production level, the field crop irrigation management decision support system, CropIrri, was established by taking account of the soil moisture prediction model, crop phenology model and irrigation decision-making model. The flowchart of CropIrri is shown in figure 1.

The CropIrri system is developed by using Visual Studio.NET 2005 language and run on the Windows XP platform.

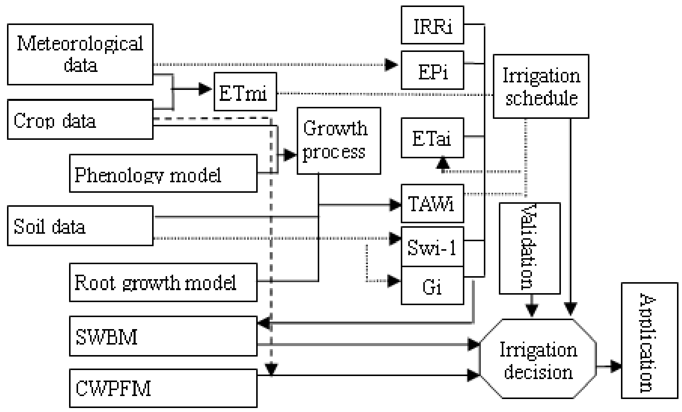

Fig.1: Irrigation flowchart for CropIrri

ETmi is maximum crop evapotranspiration on day i, SWBM is soil water balance model, CWPFM is crop water production function model.

2.1 Main function

CropIrri system is designed for dryland crops (wheat, maize and soybean) to provide a practical decision tool for irrigation management. The main functions include: (1) Irrigation decision services. To evaluate crop water requirements, and to make pre-sowing and the real-time irrigation plans based on the historical weather data and weather forecast information. (2) To simulate daily change of soil moisture content in the root zone. (3) To evaluate a given irrigation schedule, and to develop optimal irrigation schedule in addition. (4) To modify the planned results according to the measured actual soil moisture content during crop growth period to enhance the forecasting accuracy. (5) Database management capability.

2.2 Main function modules

CropIrri system combines environmental conditions like climate and soil with crop growth characteristics as a whole, and was established through soil water balance model, crop phenology model, root growth model, crop water production function, and irrigation decision-making model.

2.2.1 Soil water balance module

Soil water balance model can reflect the dynamics of soil water content in root zone and can be expressed as flow equation (Richard G Allen et al., 1998):

$$SW_i = (ETa_i + RO_i + OP_i) - (EP_i + G_i + IRR_i) + SW_{i-1} \quad (1)$$

Where: SW_i is soil water depletion in the root zone at end of the day i [mm], ETa_i is actual crop evapotranspiration on day i [mm], RO_i is runoff from the soil surface on day i [mm], OP_i is deep percolation on day i [mm], EPi is effective precipitation on day i [mm], Gi is capillary rise from the groundwater table on day i [mm], $IRRi$ is net irrigation on day i [mm], $SWi\text{-}1$ is soil water depletion in the root zone at end of the previous day, $i\text{-}1$ [mm].

(1) Initial soil water depletion (SW_{i-1})

The initial soil water depletion can be derived from measured soil water content by:

$$SW_{i-1} = 1000 \times \left(\theta_{fc} - \theta_{i-1}\right) \times Zr_{i-1} \quad (2)$$

Where:θ_{i-1} is the average soil water content for the effective root zone [m^3/m^3], θ_{fc} is the water content at field capacity [m^3/m^3].

(2) Actual crop evapotranspiration (ETai)

The calculation method of actual crop evapotranspiration is adopted from FAO-56. It equals crop water requirement multiplied by the soil water stress coefficient.

The soil water stress coefficient can be expressed by:

$$Ksi = \begin{cases} 1 & SWi < RAWi \\ \dfrac{TAWi - SWi}{TAWi - RAWi} & SWi > RAWi \end{cases} \quad (3)$$

$$TAWi = 1000 \times (\theta fc - \theta wd) \times Zri \qquad RAWi = Pi \times TAWi$$

Where: $TAWi$ is total available soil water in the root zone on day i [mm], θ wd is the water content at wilting point [m3/m3], $RAWi$ is the readily available soil water in the root zone on day i [mm], Pi is fraction of TAW that a crop can extract from the root zone without suffering water stress.

(3) Effective precipitation (EPi)

Effective precipitation is the part of natural precipitation that actually added to the crop root layer soil moisture, it is expressed by:

$$EPi = a \times TPi \qquad a = \begin{cases} 0 & TPi < 5mm \\ 1 \sim 0.8 & 5mm \le TPi \le 50mm \\ 0.7 \sim 0.8 & TPi > 50mm \end{cases} \quad (4)$$

Where: *TPi* is the forecast precipitation or natural precipitation on day *i* [mm], *a* is the rainfall recharge coefficient, Its value is related to rainfall amount, rainfall intensity, duration, soil properties, ground cover, landform and so on.

(4) Capillary rise from the groundwater table (Gi)

Capillary rise depends mainly on soil type, the depth of the water table and moisture of the root zone. General Gi can be assumed to be zero when the water table is more than about 1 m below the bottom of the root zone. Capillary rise from the groundwater table is given by:

$$Gi = ETai \times e^{-\sigma Ho} \quad (5)$$

Where:σ is experience coefficient (Sand=2.1, loam=2.0, clay=1.9), Ho is the depth of water table.

2.2.2 Crop phenology module

The predicating of crop development is the key to determine the date of irrigation. The crop phenology model was adopted from the general crop phenological theory model (CPTM) (Feng L. et al., 1999). Based on multi-annual mean meteorological data in crop growing region, the length of growth stages with different sowing date could be simulated, which is important to enhance the accuracy of parameters at different development stages.

2.2.3 Root growth module

Root growth model is used to calculate soil water content in the root zone. The planting depth (generally 0.03-0.05m) is considered as the initial crop rooting depth, maximum rooting depth (soybean is 0.6-1.3m and maize is 1-1.7m) was adopted (China's agricultural encyclopedia Agrometeorological volume Editorial Committee, 1986). The daily rooting depth of soybean and maize was interpolated by the initial and maximum rooting depth. Wheat root growth model was adopted from the flowing equation (Feng et al, 1998):

$$Zr_i = Zr \times \left(0.005628 + 2.3501 * tr - 4.5548 \times tr^2 + 3.2148 tr^3\right) \quad (6)$$

Where: Zr_i is the rooting depth on day *i* [m], *Zr* is the maximum rooting depth [m], *tr* is relative time, that means the ratio of days after sowing (on day *i*) and the number of days that roots reached the maximum rooting depth, flowering stage of winter wheat reached the maximum rooting depth.

2.2.4 Crop water production function module

The module is used for evaluating the impact of irrigation schedule on crop yield. Yield reduction is expressed by the ratio that the difference between the highest yield and the actual yield to the highest yield (highest yield means the output under non-limiting irrigation schedule). Water shortage in certain stage not only affects this period, but also affects on the whole development period. Jensen model is a high precision mathematical model in evaluating the impact of water shortage in each growth stage on crop yield under limited water supply conditions (Ge et al, 2003). Jensen model can be expressed as:

$$\frac{Ya}{Ym} = \prod_{j=1}^{n} \left(\frac{TETa}{TETm} \right)_j^{\lambda j} \tag{7}$$

Where: *Ya* is actual yield of crop [kg/ hm^2], *Ym* is maximum yield of crop [kg/ hm^2], *TETa* is actual crop evapotranspiration on stage i [m^3/hm^2], *TETm* is maximum crop evapotranspiration on stage *j* [m^3/hm^2], λ *j* is yield response factor on stage *j*, *j* is divided the whole growth period for j stages.

2.3 Modes of irrigation scheduling

Irrigation decision-making concerns the date and amount of irrigation, as well as the impact of selected irrigation schedule on crop yield. CropIrri supplies four modes of irrigation scheduling as follows.

2.3.1 Non-limiting irrigation schedule

Non-limiting irrigation is to meet the need of water requirements and to obtain maximum crop production. By comparing the daily soil moisture deficit with readily available moisture in the soil profile, when soil moisture deficit approaches readily available moisture, water stress is occurred and irrigation is made. Soil water content equaling to 80% of field capacity as suitable irrigation index was used to avoid leakage caused by deep water losses.

2.3.2 Water-saving irrigation schedule

The goal of water-saving irrigation is to obtain highest yield with highest water utilization efficiency (WUE). In this case, actual crop evapotranspiration is less than potential evapotranspiration. When soil moisture content in the root zone reached 85% ~ 90% of field capacity, it is appropriate for crop growth；When soil moisture content in the root zone below 60% of field capacity, it affects the normal growth and output of crop. In this research, the suitable soil water content in root zone ranges from 70% to 60% of field capacity in non-critical periods of of water requirement, and ranges from 75% to 65% of field capacity in critical period of water requirement. The critical period of water requirement is booting stage for wheat, flowering stage for soybean. The critical period of water requirement is from flowering stage to milk stage for maize.

When the soil moisture content in the root zone is below the appropriate low-limited water content, irrigation schedule is made to irrigate to the appropriate upper-limited water content.

2.3.3 Irrigation schedule with experience

Irrigation schedule is made by taking account into irrigation experience. In order to ensure crop emergence, priority should be given to sowing irrigation; then to consider the importance of the crop water requirement to determine irrigation plan. Taking wheat as an example, if one irrigation, irrigation should be at booting period. If two irrigations, irrigation should be at turning green stage and booting stage for the situation of irrigation at sowing, and at winter stage and booting stage for the situation of non-irrigation at sowing. If three times, irrigation should be at winter stage, turning green stage, and booting stage.

Each irrigation amount should reach the soil water content as 80% of field capacity.

2.3.4 Advanced (user custom) irrigation schedule

The mode of advanced irrigation schedule is for researchers and technicians. Users can custom the date and amount of irrigation for different purpose, such as periodic irrigation with certain amount of water, for example, irrigation with 50 mm of water or soil water content reaching to field capacity at soil moisture content decreasing to 60% of field capacity, or irrigation with 100 mm at fixed interval of 30 days. So that we can understand the change of soil moisture content and crop water consumption. This could support and assist scientific researches in crop water relation.

3. CASE STUDY FOR WHEAT CROP

The case study was conducted for irrigation management by CropIrri system during the winter wheat growing season at Quzhou experiment station, Hebei, China in 2007-2008. The historical weather data of 30 years and the measured soil data in Quzhou Experiment Station were used. Wheat variety was Han 6172, a mid-maturing wheat cultivar. The soil water content was adequate for planting wheat due to heavy rainfall before sowing. Wheat sowed on 23 October with 330×10^4/ha of basic seedlings and 3 cm of sowing depth. The measured mature date was June 3.

The pre-sowing decision-making report for winter wheat under non-limiting irrigation and water-saving irrigation is shown in Table1. Comparing the two irrigation plans, both of them irrigated in winter, which played a role in water storage to a certain extent to meet the need of soil water for winter wheat in turning green stage. Irrigation didn't apply at turning green stage in water-saving irrigation schedule, which could cause some water stress. It was a similar irrigation schedule during the jointing-flowering stages which is rapid increase in water consumption. Irrigation at this stage is conducive to yield increase. Two heavy rainfalls during wheat growth stage on April 20 and May 3 was 35 mm and 60 mm respectively. The actual irrigation under water-saving irrigation plan on the April 21 was zero.

Table 1. Report of pre-sowing irrigation plan made by CropIrri for wheat.

Irrigation plans	Growth stages	IRD (d-m)	IRR (mm)	YRR (%)
Non-limiting irrigation	Overwintering-turning green	8-Dec	39	0
	Turning green-jointing	25-Feb	44	
	Booting-flowering	18-Apr	68	
	Flowering- filling	29-Apr	61	
Water-saving irrigation	Overwintering-turning green	18-Dec	43	10.83
	Jointing-Booting	8-Apr	71	
	Booting-flowering	21-Apr	37	

IRD is irrigation date, YRR is yield reduction rate.

The experiment results and measured water data is shown in table2. Water utilization efficiency (WUE) increased 3.3% under water-saving irrigation schedule. Nearly double amount of water was saved. The final crop yield reduction was only 9.3%, which approached the predictive value of 10.83% (table1). This may be caused by the difference between multi-annual mean rainfall data with 0 mm and actual rainfall data with 60 mm on May 3. The actual rainfall helped to increase yield under water-saving irrigation plan. Over-irrigation in non-limiting irrigation plan at late growth period couldn't be all used by wheat and might waste water. Study also showed that over-irrigation decreased water use efficiency and resulted in the waste of water resource (Xu et al, 2003). The water-saving irrigation schedule had a better performance in Quzhou region and was favorable to water-saving and high yield.

Table 2. Water consumption, yield and water utilization efficiency for winter wheat under different treatments in Quzhou.

Irrigation plans	TWC	RAIN	IRR	Yield	WUE
	mm	mm	mm	kg/ha	kg/(ha.mm)
Non-limiting irrigation	472	127	212	7245.4	15.35
Water-saving irrigation	364	127	114	6570.7	18.05

TWC is total water consumption, WUE is water utilization efficiency, AAI is the actual irrigation depth.

4. CONCLUSION AND DISCUSSION

A field crop irrigation management decision-making support system was developed based on the soil water balance model, crop phenology model, root growth model, crop water production function, and irrigation management model. CropIrri system could be used in pre-sowing and real-time irrigation management decision-making support, simulation of soil water dynamics in the root zone, evaluation of the effect of certain irrigation plan on crop yield reduction, and database management. It is developed for the dryland crops of wheat, maize and soybean.

The major characteristics are to provide the different irrigation management schedules for different level of users. It not only has default irrigation schedule for the common user, also has the custom irrigation schedule that are suitable for the senior user. Through embedding crop phenology module, it could predict crop development and to support to determine irrigation date more accuracy. CropIrri system could be an objective-oriented, multi user-oriented and practical irrigation management decision-making tool.

CropIrri could allow the single crop for management decision at present. The further study is to include varying cropping patterns, such as intercropping cultivation to enhance its function.

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