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Modeling maize planting date to minimize irrigation water requirements

[1]Eric. Y. Kra and *[2]J. Ofosu-Anim

[1] Agricultural Engineering Department, University of Ghana, Legon, Ghana
[2] Crop Science Department, University of Ghana, Legon, Ghana

*Corresponding author: aweze@ug.edu.gh

Abstract

A mathematical model that uses daily maximum and minimum temperature data is presented for selecting the best planting day to minimize the total irrigation water required to grow corn. The model calculates the total seasonal irrigation water requirement by summing the daily crop evapotranspiration, ET_c, soil moisture storage and deep percolation losses from the planting date to the harvest date. The planting date resulting in the lowest irrigation water requirement for the growing season was selected as the best date to plant the crop in order to maximize total irrigable area for the available quantity of irrigation water, or to minimize the required irrigation water for the given area. The model was used to simulate the seasonal cropwater requirements of maize using 1998-2008 daily weather data from a weather station in the Coastal Savannah zone of Ghana. The optimum planting dates were found to be between 15th March and 15th May, and the worst planting dates 2nd November and 14th January. The differences between irrigation water requirements between the optimum and worst planting dates were 57~95%, implying that up to about 95% more area could be irrigated without additional irrigation water through optimum planting date selection. The coincidence of the model optimum planting window with the indigenous planting time indirectly validates the the 1985-Hargreaves reference evapotranspiration sub-model for this part of the world.

Keywords: Evapotranspiration; cropwater requirements; irrigation; weather data; maize; planting date; extraterrestrial radiation; Hargreaves equation

Abbreviations

d_r^i — relative earth-sun distance; d_{rs}^i — season depth of rainfall for planting day i (mm); dp_s^i — seasonal deep percolation below soil root zone for planting day i (mm); ET_c^i — crop evapotranspiration (mm/day); ET_o — reference grass evapotranspiration (mm/day); FAO — Food and Agriculture Organization of the United Nations; G_{sc} — global solar constant (MJ m^{-2} min^{-1}); h — day of harvest; ^{i} — superscript, denotes the value of the variables on day i; Ir_s^i — seasonal irrigation water requirement for planting day i (mm); J^i — Julian day of the year of day i (Jan 1 = 1); k_c — crop coefficient; $_s$ — subscript, denotes seasonal value of the subscripted variable; R_A —extraterrestrial radiation (MJ m^{-2} d^{-1}); T_{avg} — average daily temperature ($^\circ$C); T_{max} — maximum daily temperature ($^\circ$C); T_{min} — minimum daily temperature ($^\circ$C); ΔS_s^i — seasonal net change in soil moisture storage for planting day i (mm); δ^i — solar declination (radians); ϕ — latitude (radians); ω_s^i — sunset hour angle (radians).

Introduction

There is increasing pressure on the agricultural sector to feed the growing world population. This pressure is exacerbated by the increasing competition for freshwater from municipal and industrial sectors. Obviously because of the limited freshwater resources of the earth the solution does not lie

Table 1. Crop coefficients and length of growth states for early-, and late-maturing corn.

Growth stage	Length of growth stage		Crop k_c
	Early-maturing	Late-maturing	
Initial	16	20	0.7
Development	30	35	linearly interpolated
Mid-season	34	40	1.2
Late season	25	30	linearly interpolated
Harvest	N/A	N/A	0.6
Total	105	125	

Data source: Allen et al. (1998) and Tweneboah (2000)

in discovering more freshwater resources but rather in using the currently available water more efficiently. One very effective way of using available water resource more effectively in agriculture is to minimize the amount of irrigation water required to grow a crop, not only by the traditional methods of reducing conveyance and application losses, but also by reducing the cropwater requirement itself through using planting dates that result in minimal growing period supplementary irrigation water requirements. Many sophisticated models have been created for modeling plant growth such as the CEREZ and RZWQM models (Anapalli et al., 2005).

Numerous sophisticated models that can be used for improving water use efficiency already exist, but as Bastiaanssen et al. (2004) point out, the implementation of these models has had a very poor track record over the past quarter of a century for various reasons. After many years of farming indigenous farmers have developed their own methods of determining planting dates that take into account many local conditions that numerical models do not and hence the reluctance of extension agents and policy makers to use them. Another reason of course is the sophistication of many of these models. However in these days of changing climates indigenous knowledge alone cannot be used to make the fine adjustments in planting dates that are necessary for the large improvements in water use efficiency that are needed to improve agricultural productivity. The purpose of this paper then is to show by using an irrigation water requirement model that is simple enough to be understood and accepted by many non-technical extension agents and policy makers that these models do agree in general with the indigenous knowledge of traditional farmers. Once confidence has been created the models can then be used as tools to improve water use efficiency.

A very important component of a cropwater use model is the estimation of crop evapotranspiration. Many sophisticated models exist, the most reliable of which is generally accepted to be the FAO recommended Penman-Monteith model (Allen et al., 1998, 2007), but the data requirements keep it beyond the use of many developing country situations where poor data is the norm rather than the exception. Fortunately, a simpler alternative exists that requires only maximum and minimum temperature data-the Hargreaves model (Hargreaves,1994; Droogers and Allen, 2002). This paper used this simpler model to estimate reference evapotranspiration which was then converted to crop evapotranspiration using the simple single-kc approach of Allen et al. (1998). Then applying the law of conservation of mass to the soil root zone, accounting for deep percolation and and soil moisture storage, the net total growing period irrigation water requirement was computed for each day of the years 1998 to 2007. For each year the optimal planting date was selected as the planting day that resulted in the least irrigation water requirement.

Materials and methods

The methodology consists of using weather data to compute the water requirements of maize crops planted on every day of the year. The seasonal cropwater requirement for any planting day is the sum of the water requirements for every day starting from the day of planting to the day of harvest. The optimum planting date of each year was selected as the day of planting of the year that resulted in the lowest seasonal cropwater requirement. The best planting date model developed in this study consists of four sub-models:

1. A model to compute the grass reference evapotranspiration for each day of the year, the ET_o sub-model;
2. A model to compute the extraterrestrial radiation for each day of each year, the R_A sub-model;
3. A model to compute the cropwater requirement of maize, the ET_c sub-model; and
4. A model to compute the seasonal irrigation water requirements, the Ir_s sub-model.

Extraterrestrial radiation sub-model

The extraterrestrial radiation, R_A, which depends mainly on the Julian day of year (DOY) and the latitude of the location, was calculated using the set

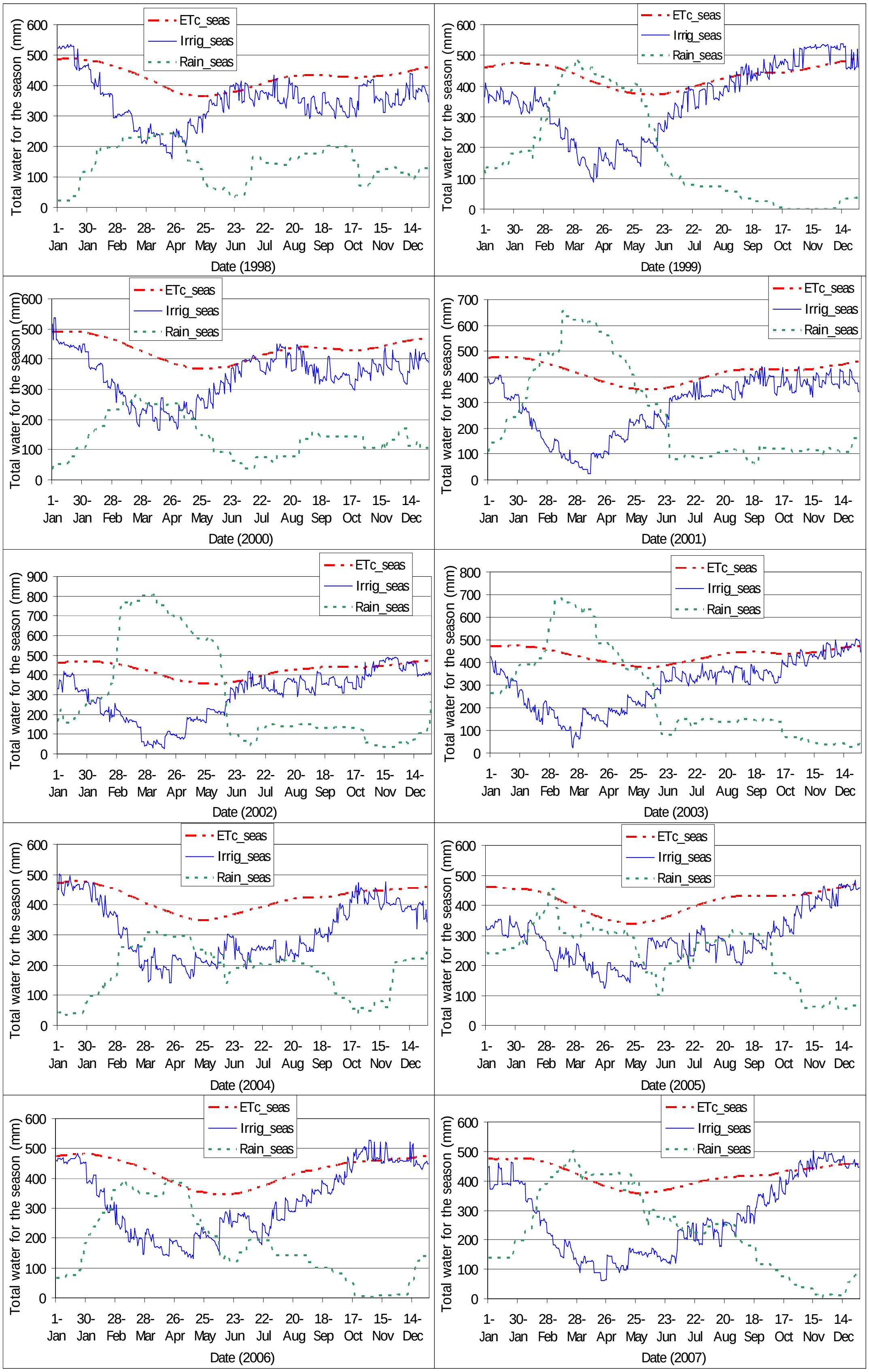

Fig 1. Computed seasonal irrigation water requirements for 105-day maturity corn for planting dates in 1998-2007.

of equations presented by Duffie and Beckman (1991):

$$R_A^i = \frac{24\times 60}{\pi} G_{sc} d_r [\omega_s \sin(\phi)\sin(\delta^i) + \cos(\phi)\cos(\delta^i)\sin(\omega_s^i)] \quad (1)$$

$$\delta^i = 0.4093 \sin\left(\frac{2\pi(284 + J^i)}{365}\right) \quad (2)$$

$$d_r^i = 1 + 0.033\cos\left(\frac{2\pi J^i}{365}\right) \quad (3)$$

$$\omega_s^i = \cos^{-1}(-\tan(\phi)\tan(\delta^i)) \quad (4)$$

where G_{sc} = global solar constant 0.0820 (MJ m $^{-2}$ min $^{-1}$); R_A^i = extraterrestrial radiation (MJ m $^{-2}$ d $^{-1}$); J^i = Julian day of the year of day i (Jan 1 = 1); d_r^i = relative earth-sun distance; ω_s^i = sunset hour angle (radians); ϕ = latitude (radians); δ^i = solar declination (radians). The superscript i, denotes the value of the variables on day i.

The ET_o sub-model

ET_o was calculated for each day of the year using the Hargreaves(1994) reference evapotranspiration model (Droogers and Allen,2002):

$$ET_o^i = 0.0023\times 0.408(T_{avg}^i + 17.8)(T_{max}^i - T_{min}^i)^{0.5} R_A^i \quad (5)$$

where T_{max} = maximum daily temperature ($^\circ$ C); T_{min} = minimum daily temperature ($^\circ$ C); T_{avg} = average daily temperature ($^\circ$ C); and R_A = extraterrestrial radiation (MJ m $^{-2}$ d $^{-1}$). In Equation **Error! Reference source not found.**, the superscript i refers to the value of the particular parameter on day i.

There are more elaborate ET_o models such as the FAO-recommended Penman-Monteith which is used in several computer software like CROPWAT (Smith,1992) and RefET (Allen,2000), but the Hargreaves model was selected for this phase of the research because it requires minimal weather data: maximum and minimum temperatures.

The ET_c -sub-model

The *daily* crop water requirements were calculated using the single crop coefficient method of Allen et al. (1998):

$$ET_c^i = k_c^i \times ET_o^i \quad (6)$$

where ET_c^i = crop evapotranspiration on the i th day (mm/day); ET_o = reference grass evapotranspiration on day i (mm/day), and k_c = the crop coefficient. The simple linear k_c procedure of Allen et al. (1998, 2007) was used, assuming the lengths of the various stages of maize and their corresponding growth seasons shown in table 1.

The *seasonal* water requirement for a crop planted on day i, ET_{cs}^i, was calculated as the sum of the daily crop water requirements from day planting day, i, to harvest day h:

$$ET_{cs}^i = \sum_{i=1}^{h} ET_c^i = \sum_{i=1}^{h} k_c^i ET_o^i \quad (5)$$

The irrigation water requirement sub-model

The seasonal irrigation water requirement for planting day i, Ir_s^i, is the water that must be supplied by irrigation to meet the evapotranspiration and soil moisture storage requirements of the crop which is not under water-stress, after accounting for rainfall and deep percolation losses:

$$Ir_s^i = ET_{cs}^i - d_{rs}^i + dp_s^i + \Delta S_s^i \quad (6)$$

where dp_s^i is the deep percolation for the growing season starting on day i; d_{rs}^i = depth of rainfall over the growing period for planting day i; ΔS_s^i = net change in soil moisture storage over the entire root zone between the day of planting and the harvest day, h. The root zone was assumed to be 0.10 m at the time of planting and to grow linearly from there to its maximum depth of 0.9 m at the middle of the mid-season stage of growth. The management allowable soil moisture deficit was taken as 0.5 and the initial soil moisture content of the entire root zone as half the maximum soil moisture capacity. Deep percolation was accounted whenever the soil moisture exceeded the maximum moisture capacity of the entire root zone after rainfall.

Table 2. Planting days of minimum seasonal irrigation and cropwater requirements for 105-day-maturity corn for 1998-2007.

	Ir_s^{min}	Ir_s^{min}	Ir_s^{max}	Ir_s^{max}	ET_{cs}^{min}	ET_{cs}^{min}	ET_{cs}^{max}	ET_{cs}^{max}	$Max - Min$ (%)	
Year	(mm)	dd-mm-yy	(mm)	dd-mm-yy	(mm)	dd-mm-yy	(mm)	dd-mm-yy	Ir_s	ET_{cs}
1998	159	23-Apr-98	534	14-Jan-98	364	26-May-98	490	16-Jan-98	70	26
1999	89	17-Apr-99	539	14-Dec-99	371	17-Jun-99	489	31-Dec-99	84	24
2000	163	13-Apr-00	537	3-Jan-00	368	26-May-00	491	27-Jan-00	70	25
2001	24	10-Apr-01	441	2-Nov-01	351	5-Jun-01	478	20-Jan-01	94	27
2002	28	15-Apr-02	489	27-Nov-02	355	6-Jun-02	473	24-Dec-02	94	25
2003	25	23-Mar-03	505	27-Dec-03	378	4-Jun-03	476	26-Jan-03	95	21
2004	141	21-Apr-04	502	3-Jan-04	349	21-May-04	478	21-Jan-04	72	27
2005	123	27-Apr-05	484	26-Dec-05	338	22-May-05	472	31-Dec-05	75	28
2006	131	15-May-06	526	4-Nov-06	346	14-Jun-06	483	30-Jan-06	75	28
2007	63	24-Apr-07	502	16-Nov-07	357	2-Jun-07	476	5-Feb-07	87	25

Table 3. Planting days of minimum seasonal irrigation and cropwater requirements for 125-day-maturity corn for 1998-2007.

	Ir_s^{min}	Ir_s^{min}	Ir_s^{max}	Ir_s^{max}	ET_{cs}^{min}	ET_{cs}^{min}	ET_{cs}^{max}	ET_{cs}^{max}	$Max - Min$ (%)	
Year	(mm)	dd-mm-yy	(mm)	dd-mm-yy	(mm)	dd-mm-yy	(mm)	dd-mm-yy	Ir_s	ET_{cs}
1998	241	21-Apr-98	558	5-Jan-98	441	7-May-98	576	5-Jan-98	57	23
1999	138	1-Apr-99	626	11-Nov-99	448	2-Jun-99	576	28-Dec-99	78	22
2000	227	13-Apr-00	549	14-Jan-00	445	23-May-00	577	4-Jan-00	59	23
2001	64	23-Mar-01	522	29-Oct-01	423	30-May-01	561	7-Jan-01	88	25
2002	53	26-Mar-02	555	10-Nov-02	431	23-May-02	560	24-Dec-02	90	23
2003	113	15-Mar-03	582	20-Dec-03	457	19-May-03	559	24-Dec-03	81	18
2004	204	1-Apr-04	575	10-Jan-04	424	13-May-04	560	10-Jan-04	65	24
2005	177	9-Apr-05	559	19-Dec-05	411	18-May-05	564	31-Dec-05	68	27
2006	172	25-Apr-06	593	29-Oct-06	419	2-Jun-06	567	10-Jan-06	71	26
2007	93	31-Mar-07	584	29-Nov-07	432	21-May-07	566	6-Jan-07	84	24

Crop and weather data

Daily maximum and minimum temperature and rainfall data for January 1998 to August 2008 from a meteorological weather station in Accra located at latitude 5.55 degrees north and longitude 0.7, were used. The k_c values for maize, maturing in 125 days, were obtained from Allen et al. (1998), where values are given for the initial, mid-season, and maturity periods. For this study, since no published local data or functions were located, it was assumed that k_c varied linearly between the end of the initial season and the start of the mid-season, and also between the end of the mid-season and harvest (see Table 1).

The main assumptions in the study were that the following were not affected by planting date:

1. The lengths of the growing seasons of the 105-day-, and 125-day-maturity corn;
2. The crop coefficient curve;
3. The root growth curve.

In Ghana the early maturing corn varieties have a growing period of 105 days and the late maturing, about 125 days Tweneboah (2000). The root depth of the maize was assumed to increase linearly from a planting depth of 0.05 m (Onwueme and Sinha, 1991) to a maximum of 0.9 m at the mid-point of the mid-season of crop growth (Keller and Bliesner, 1991). The lengths of the growth stages for the 105-maturing corn variety was assumed to be proportional to those maturing in 120 days.

The computer program

The model was programmed in Microsoft Visual Basic for Applications in Microsoft Excel and run on a Hewlett-Packard dv6000 computer.

Results and discussion

The results of the total seasonal cropwater and irrigation water requirements and rainfall versus planting date simulations are summarized in Tables 2-3. The variations of the seasonal irrigation and cropwater requirements, and rainfall for the years 1998-2007 are shown in Figs. 1 and 2 for 105-day-, and 125-day-maturity corn.

The seasonal water requirements shown in the Figs. and Tables are not the water requirements for the particular days, but rather the sum of the cropwater requirements for all the days of the growing season, 105 days or 125 days.

In general, Ir_s^i varied throughout the year, but its shape was similar for all the years of data, falling from the beginning of the year to a minimum value between March and April and then rising again with time for the rest of the year. In general the trend of the seasonal irrigation water requirement was opposite that of the seasonal rainfall, though their maximum and peaks did not coincide. The shape of ET_{cs}^i curves were similar for each year falling from a high value in January to a low in May-June, and then rising thereafter for the rest of the year. It is noted that during some parts of the year the $Ir_s^i > ET_{cs}^i$, which is to be expected since part of the irrigation water is stored in the soil between irrigations and the soil moisture at the end of the season is usually higher than it was was at the time of planting because the initial soil moisture was not field capacity but rather 50% of field capacity. The exceeding of ET_{cs}^i by Ir_s^i is more pronounced during periods of low rainfall, e.g., October-December 1999.

The minimum values of Ir_s^i occurred between 23 rd March and 15 th May for the 105-day-maturity corn and 15 th March and 25 th April for the 125-day-maturity corn variety. The Ir_s^{min} value was not always very distinct as can be seen from the curves for the 105-day-maturity curves for 2004-2007, but in general the period during which it is low also coincides with the successful rainfed traditional maize planting season in the Coastal Savannah zone of Ghana. This coincidence indirectly partially validates the use of the Hargreaves (1994) reference evapotranspiration model for this region when there is inadequate reliable data to use the more generally reliable Penman-Monteith model of Allen et al. (2007).

The maximum values of Ir_s^i occurred between 2nd November and 14th January for the 105-maturity corn and between 10th November and 14th January for the 125-day-maturity corn. The water savings of planting on the Ir_s^i day over planting on the high Ir_s^i was 70~95% for the 105-day corn and 57~90% for the 125-day corn and (Tables 2 and 3), implying that as much as 95% more land could

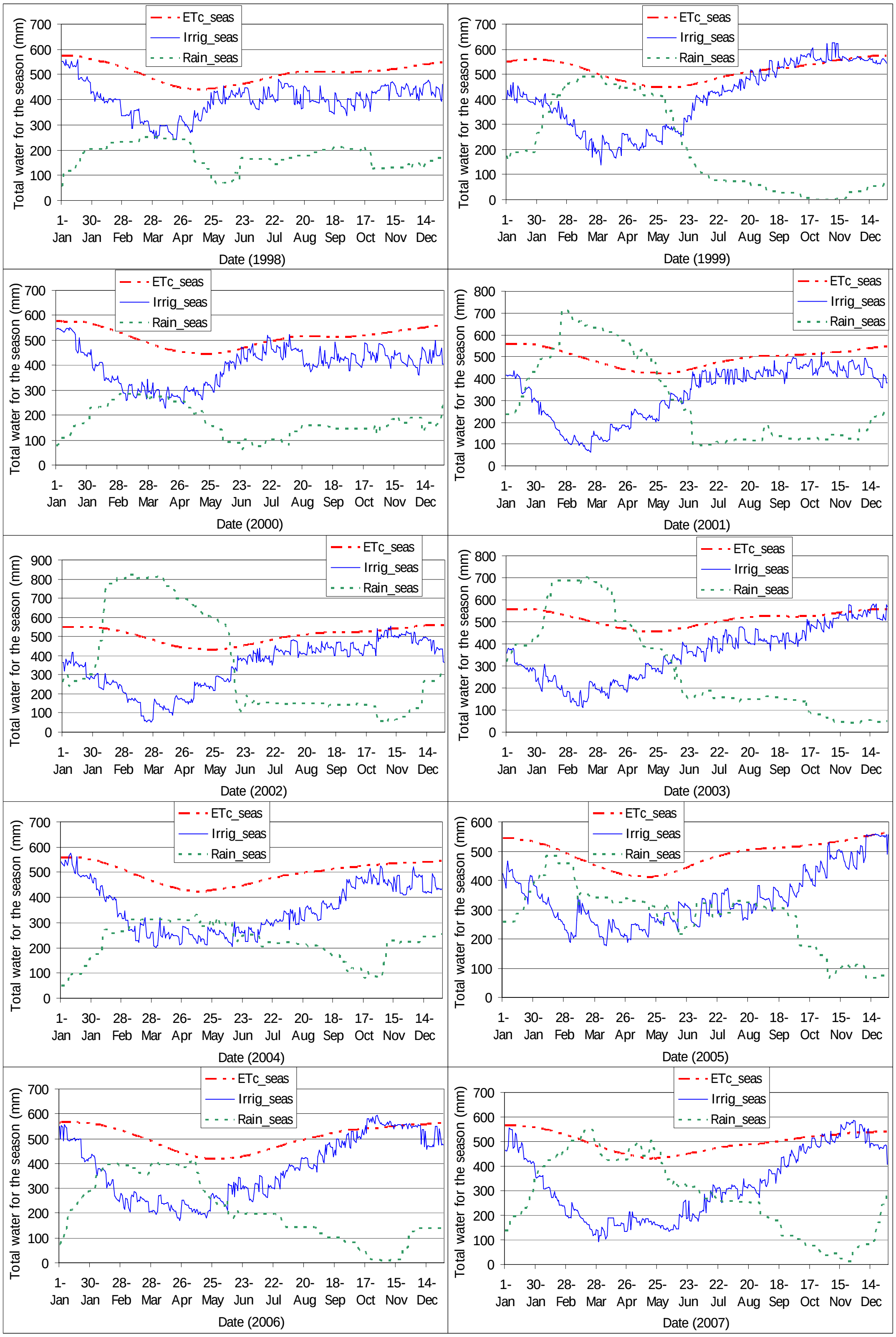

Fig 2. Computed seasonal irrigation water requirements for 125-day maturity corn for planting dates in 1998-2007.

irrigated with the same amount of water simply by changing the planting date.

Conclusions and Recommendations

The results of the simulation reported in this paper have demonstrated that the differences between the irrigation water required to grow corn in the Coastal Savannah region of Ghana could be as high as 95% if the optimum planting date is selected. The best time to plant maize in this zone to minimize irrigation water requirements from 1998 to 2007, was between 15th March and 15th May. Planting maize between 2nd November and 14th January required the highest irrigation water amounts. The computed optimum period for growing maize also coincides with the traditional rain-fed corn planting period in this region of Ghana. The model could therefore be used for planning purposes to predict water savings from planting on certain days of the year. It is however noted that the weather data used in this study was from only one weather station, therefore the results may not be generally applicable for the whole region without further study. But the coincidence of the simulated optimum planting window and no-planting windows with the planting times of local farmers indirectly validates, the 1985-Hargreaves ET equation (Hargreaves,1994) for use for reference grass evapotranspiration estimation for this part of the world, when reliable data is not available to use the FAO-recommended Penman-Monteith equation (Allen et al., 2007).

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