Rationale of Deficit Irrigation Planning and Management

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Abstract

A simulation model for evaluating the effect of water availability in the soil and salinity on yield under deficit irrigation has been developed. The model is based on water volume balance concept for scheduling irrigation using different levels of allowable percent water depletion. To take the effect of salinity on yield into consideration, the crop evapotranspiration is linked to the salinity level in the soil water using the procedure described in FAO (1998). The model was used to study the effect of both water deficit and salinity build-up during the growing season on yield of cotton for different scenarios, assuming zero leaching, with different irrigation water salinity levels, and allowable percent depletion of water in the root zone.

To verify the validity of the model, preliminary one year data from experiment conducted in northern Syria during the summer season of year 2004 for cotton are used. The data included four deficit irrigation levels using drip irrigation system: full irrigation (no deficit); applying 80%, 60%, and 40% of full irrigation. The experiment was laid out in three replications. The main outcome of the study included useful relationships between relative yield with relative crop evapotranspiration as affected by different levels of deficit irrigation and water salinity. Given the salinity of irrigation water and selecting a cretin level of percent water depletion, the relative evapotranspiration (Et_{cadj}/ET_c) can be predicted. Upon knowing the relative evapotranspiration, the relative yield under the given conditions can be also evaluated.

Keywords: deficit irrigation, irrigation scheduling, soil salinity, simulation, evapo-transpiration, leaching requirements.

الإدارة والتخطيط العقلاني للري الناقص

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الخلاصة

تم تطوير نموذج محاكاة لحساب تأثير توفر الماء في التربة وملوحته على الأنتاج تحت ظروف الري الناقص. يعتمد النموذج على فرضيات الموازنة المائية الحجمية لبرمجة الأرواء بأستخدام مستويات مختلفة من نسبة استنزاف الماء في المنطقة الجذرية للنبات. لأخذ تأثير الملوحة على الأنتاج بنظر الأعتبار، تم ربط التبخر نتح للنبات مع مستوى الملوحة في ماء التربةبأستخدم الطريقة المقترحة من قبل منظمة الأغذية والزراعة الدولية (FAO,1998). تم استخدام نموذج المحاكاة لدراسة تأثير الري الناقص والملوحة على انتاج محصول القطن ولعدة حالات تتضمن مستويات مختلفة لملوحة ماء الري ونسبة الأستنزاف الرطوبي من المنطقة الجذرية للنبات على فرض عدم وجود أي غسل للأملاح من التربة. وللتأكد من دقة نموذج المحاكاة، تم تطبيقه على نتائج تجربة حقلية أجريت شمال سوريا خلال صيف عام ٢٠٠٤ وعلى محصول القطن. تضمنت البيانات أربعة مستويات من الري الناقص لمحصول القطن تم زراعته خلال الموسم الصيفي لعام ٢٠٠٤. واجريت التجربة بثلاث مكررات أستخدم فيها نظام الري بالتنقيط وتحت أربع مستويات للري الناقص كانت على التوالي ٦٠، ٤٠، ٢٠، و ٠%. تضمنت النتائج الرئيسية للدراسة ايجاد علاقة تربط بين الأنتاج النسبي للمحصول مع الأستهلاك المائي النسبي وتحت تأثير عدة مستويات من الري الناقص وملوحة ماء الري. من معرفة ملوحة ماء الري وبأختيار مستوى استنفاذ الرطوبة يمكن حساب الانتاج النسبي للمحصول(ET_{cadj}/ET_c).ومن معرفة الأستهلاك المائي النسبي للمحصول يمكن معرفة الأنتاج النسبي للمحصول تحت نفس الظروف والفرضيات.

Received 1st April 2006　　Accepted 23 July 2006

Introduction

Deficit irrigation is an optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. The adoption of deficit irrigation implies appropriate knowledge of crop water use and responses to water deficits, including the identification of critical crop growth periods, and of the economic impacts of yield reduction strategies. The available results show significant improvement in water productivity at lower application rates than at full irrigation.

Experience from Syria showed that applying only 50% of the rainfed wheat irrigation requirements reduces yield by only less than 15%. The decision on optimal strategies under varying conditions is a complex one, especially in rainfed areas where rainfall is varying in amount and distribution. There is real need to determine the levels of irrigation water to which the crop be under-irrigated without reducing income below that which would be earned for full irrigation under limited water resources.

Under deficit irrigation, soil moisture monitoring becomes extremely critical due to:

1. The issue of non-uniformity of irrigation water distribution in the field becomes more serious. Averaging a basically non-uniform deficit over the field may result in risky levels of under irrigation in parts of the field. Under surface irrigation, the deficit accumulates with time (i.e. along the season). However, under sprinkling and due to the effect of wind variation on water distribution, the risk of deficit accumulation is much less.
2. Salinity problem in water and soil becomes more pronounced. Maintaining a favorable salt balance in the root zone has a direct bearing on crop production and water use efficiency (yield per unit volume of water consumed by crop).

Deficit irrigation has proved been success with a number of crops in various parts of the world. These crops are relatively resistant to water stress, or they can avoid stress by deep rooting, allowing access to soil moisture lower in the soil profile. English and Raja (1996) described three deficit irrigation case studies in which the reductions in irrigation costs were greater than the reductions in revenue due to reduced yields. Deficit irrigation can lead, in principle, to increased profits where water costs are high or where water supplies are limited. Under these circumstances, deficit irrigation can be a practical choice for growers.

Deficit irrigation is one way of maximizing water use efficiency (WUE) for higher yields per unit of irrigation water applied**.** Irrigation scheduling based on deficit irrigation requires careful evaluation to ensure enhanced efficiency of use of increasingly scarce supplies of irrigation water. Much published research has evaluated the feasibility of deficit irrigation and whether significant savings in irrigation water are possible without significant yield penalties. The main objective of deficit irrigation is to increase the WUE of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

Cotton shows complex responses to deficit irrigation because of its deep root system and its ability to maintain low leaf water potential. Thomas et al. (1976) found that plants that suffered a gentle water stress during the vegetative period showed higher tolerance of water deficit imposed later as a result of adaptation to existing soil water status. Grimes and Dickens (1977) reported that both early and late irrigations lowered cotton yields. However, water stress during vegetative growth, causing leaf water potential less than a critical midday value of -1.6 MPa , adversely affected the final yield (Grimes and Yamada, 1982).

Water stress may be imposed during specific growth stages of the crop that are insensitive to water shortage. In general, four physiological growth stages for each crop are sufficient to describe their sensitivity to water stress: (a) initial (planting to 10 percent ground cover); (b) crop development (10 percent ground cover to effective full cover and initiation of flowering); (c) mid-season (effective soil cover to onset of maturity); (d) late season (onset of maturity to harvest), (FAO, 1998).

The relationships between crop yields and water use are complicated. Yield may depend on time at which water is applied or on the amount. Information on optimal scheduling of limited amounts of water to maximize yields of high quality crops is essential if irrigation water is to be used most efficiently (Al-Kaisi et al., 1997). The various crop development stages possess different sensitivities to moisture stress (FAO, 1979; English and Nakamura, 1989; Ghahraman and Sepaskhah, 1997). Timing, duration and the degree of water stress all affect yield.

Objective

An attempt is made to tackle the following issues related to deficit irrigation:

1. Building a simulation model to assess the economical feasibility of different levels of deficit irrigation under uniform irrigation with no salinity problems.
2. Extend the model to include the effect of water salinity on planning and management of deficit irrigation.

Model Description

Forces acting on soil water decrease its potential energy and make it less available for plant root extraction. When the potential energy of soil water drops below a threshold value, the crop is said to be water stressed. The effects of soil water stress on crop evapotranspiration are reflected by multiplying the basal crop coefficient by the water stress coefficient, Ks:

$$ETc_{adj} = (K_s \times K_{cb} + K_e) \times ET_o \text{..................................(1)}$$

where:

K_s = water stress coefficient

K_{cb} = basal crop coefficient

K_e = soil evaporation coefficient

$ET_{c\ adj}$ = actual crop evapotranspiration under water stress conditions(mm/day)

ET_o = reference crop evapotranspiration (mm/day)

If there is no soil water stress, K_s=1. For soil water limited conditions, $K_s < 1$.

The coefficient K_s describes the effect of water stress on crop transpiration. Where the single crop coefficient is used, the effect of water stress is incorporated into K_c as :

$$ETc_{adj} = K_s \times K_c \times ET_o \text{.......... ....} (2)$$

where:

K_c = crop coefficient

Soil Water Availability

Total available water (TAW)

Soil water availability refers to the capacity of a soil to retain water available to plants. The water content in the root zone decreases as a result of water uptake by the crop. The potential total available water in the root zone at any time during the growing season is the difference between the water content (in units of depth) at field capacity and at wilting point:

$$TAW(t) = 1000 \times (Q_{fc} - Q_{wp}) \times Zr \text{.......... ....} (3)$$

Where

TAW(t) = the total available soil water in the root zone (mm) at any time, t

Q_{fc} = the water content at field capacity ($m^3\ m^{-3}$)

Q_{wp} = the water content at wilting point ($m^3\ m^{-3}$)

Z_r = the rooting depth (m)

TAW is the amount of water that a crop can extract from its root zone, and its magnitude depends on the type of soil and the rooting depth .

Readily Available Water (RAW)

Where the soil is sufficiently wet, the soil supplies water fast enough to meet the atmospheric demand of the crop, and water uptake equals ET_c. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to experience stress. The fraction of *TAW* that a crop can extract from the root zone without suffering water stress is the readily available soil water which can be expressed as follows:

$$RAW = p \times TAW \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where :

RAW = the readily available soil water in the root (mm)

P = average fraction of total available soil water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs ,ranges between zero and one.

A numerical approximation for adjusting *p* for Etc rate different than 5 mm/day is :

$$p = p(table) + 0.04 \times (5 - ETc) \ldots\ldots\ldots \quad \ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots\ldots \quad (5)$$

Where:

p(table) is taken from Table 22 in FAO (1998).

Water Stress Coefficient (Ks)

The effect of soil water stress on crop evapotranspiration is described by reducing the value for the crop coefficient. Water content in the root zone can be expressed by root zone depletion, *Dr*. At field capacity, the root zone depletion is zero (*Dr* = 0). When soil water is extracted by evapotranspiration, the depletion increases and stress will be induced when *Dr* becomes equal to *RAW*. After the root zone depletion exceeds *RAW*, the root zone depletion becomes high enough to limit evapotranspiration to less than potential values and the crop evapotranspiration begins to decrease in proportion to the amount of water remaining in the root zone.

For *Dr* > *RAW*, Ks is given by:

$$K_s = \frac{(TAW - D_r)}{(TAW - RAW)} = \frac{(TAW - D_r)}{((1-p) \times TAW)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where :

K_s = dimensionless transpiration reduction factor dependent on available soil water (0 – 1) .

Soil Water Balance

The estimation of K_s requires daily water balance computation for the root zone. The root zone can be represented by a container in which the water content may fluctuate. The daily water balance expressed in terms of depletion at the end of the day (i) is:

$$D_{r,i} = D_{r,i-1} + ET_{cadj,i} \text{..........} \quad \text{..........} \quad \text{..........} \quad \text{..........} \quad \text{..........} \quad ..(7)$$

Where :

$D_{r,i}$ = root zone depletion at the end of day i (mm)

$D_{r,i-1}$ = water content in the root zone at the end of the previous day,i-1 (mm)

$ET_{cadj,i}$ = crop evapotranspiration on day i (mm)

By assuming that the root zone is at field capacity following irrigation, the minimum value for depletion $D_{\mathrm{r,i}}$ is zero. As a result of percolation and evapotranspiration, the water content in the root zone will gradually decrease and the root zone depletion will increase. In the absence of any wetting (irrigation or rain) event, the water content will steadily reach its minimum value Q_{WP}. At that moment no water is left for evapotranspiration in the root zone, K_s becomes zero, and the root zone depletion has reached its maximum value TAW . The limits imposed on $D_{\mathrm{r,i}}$ are consequently :

$$0 \leq D_{r,i} \leq TAW \quad \text{..........} \quad \text{..........} \quad \text{..........} \quad \text{..........} \quad \text{..........} \quad ......(8)$$

To initiate the water balance for the root zone in the simulation model, the initial depletion $D_{\mathrm{r,i-1}}$should be estimated. The initial depletion can be derived from measured soil water content by:

$$D_{r,i-1} = 1000 \times (Q_{FC} - Q_{i-1}) \times Z_r \text{...(9)}$$

Where Q_{i-1} is the average soil water content for the effective root zone. Following

Heavy rain or irrigation, the user can assume that the root zone is near field capacity, i.e., $D_{r,0}$=zero .

Borg and Grimes (1986) found that the increase in rooting depth with time delineates a sigmoid curve for a wide variety of crops and growing conditions Eq. (10).The following function has been proposed to describe the variation of the effective root zone depth with time:

$$Zr = Zr_{\max}\left[0.5 + 0.5\sin\left(3.03\frac{DAP}{DTM} - 1.47\right)\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

where :

$Zr_{\max}$ = Maximum rooting depth(cm)

DAP = Current day after planting

DTM = Days to maturity

Effect of Soil Salinity

Salts in the soil water solution can reduce evapotranspiration by making soil water less "available" for plant root extraction. Salts have an affinity for water and hence additional force is required for the crop to extract water from a saline soil. In addition, some salts cause toxic effects in plants and can reduce plant metabolism and growth.

FAO (1998) presented a function that predicts the reduction in evapotranspiration caused by salinity of soil water.

The function is derived by combining yield – salinity equations from the FAO (1976) with yield – ET equations from FAO (1979). The resulting equation provides an approximation of the reduction in evapotranspiration expected under various salinity conditions. Under optimum management conditions, crop yields remain at potential levels until a specific, threshold electrical conductivity of the soil water solution is reached. When salinity increases beyond this threshold, crop yields are presumed to decrease linearly in proportion to the increase in salinity. The soil water salinity is expressed as the electrical conductivity of the saturation extract, EC_e. In equation form, the procedure proposed by the FAO (1976) is:

$$\frac{Y_a}{Y_m} = 1 - (EC_e - EC_{\mathrm{e\ threshold}})\frac{b}{100} \quad \text{..(11)}$$

for conditions where $EC_e > EC_{e\ \mathrm{threshold}}$ where :

Y_a = actual crop yield

Y_m = maximum expected crop yield when $EC_e < EC_{e\ \mathrm{threshold}}$

EC_e = mean electrical conductivity of the saturation extract for root zone [dS m^{-1}]

$EC_{\mathrm{e\ threshold}}$ = electrical conductivity of the saturation extract at the threshold of EC_e

when crop yield first reduces below Y_m [dS m^{-1}]

b = reduction in yield per unit increase in EC_e [%/(dSm^{-1})]

Values for $EC_{\mathrm{e\ threshold}}$ and b have been provided in Table 23 of the FAO (1998) for many agricultural crops.

Since salt concentration changes as the soil water content changes, soil salinity is normally measured and expressed on the basis of the electrical conductivity of the saturation extract of the soil (EC_e). The EC_e is defined as the electrical conductivity of the soil water solution after the addition of a sufficient quantity of distilled water to bring the soil water content to saturation. EC_e is typically expressed in decisiemens per meter (dS m^{-1}). Under optimum management conditions, crop yields remain at potential levels until a specific, threshold electrical conductivity of the saturation soil water extract ($EC_{e\ threshold}$) is reached. If the average EC_e of the root zone increases above this critical threshold value, the yield is presumed to begin to decrease linearly in proportion to the increase in salinity. The rate of decrease in yield with increase in salinity can be estimated by Eq. (11).

All plants do not respond to salinity in a similar manner; some crops can produce acceptable yields at much higher soil salinity levels than others. This is because some crops are better able to make the needed osmotic adjustments that enable them to extract more water from a saline soil, or they may be more tolerant of some of the toxic effects of salinity. Salt tolerance for many agricultural crops are provided in the FAO (1979) and FAO (1993). The $EC_{e,\ threshold}$ and slope b from these sources are listed in Table 23 of the FAO (1998).

Yield – moisture stress relationship

A simple, linear crop- water production function was introduced in the FAO (1979) to predict the reduction crop yield when crop stress was caused by a shortage of soil water:

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_{cadj}}{ET_c}\right)\text{..}(12)$$

where :

K_y = a yield response factor [-]

ET_{cadj} = adjusted (actual) crop evapotranspiration [mm d^{-1}]

ET_c = crop evapotranspiration for standard conditions (no water stress) [mm d^{-1}]

K_y is a factor that describes the reduction in relative yield according to the reduction in ET_c caused by soil water shortage.

In FAO (1979), K_y values are crop specific and may vary over the growing season. In general, the decrease in yield due to water deficit during the vegetative and ripening period is relatively small, while during the flowering and yield formation periods it will be large. Values for K_y for individual growth periods and for the complete growing season have been included in the FAO (1979).

Combined salinity- ET reduction relationship

No water stress (D_r < RAW)

When salinity stress occurs without water stress, Equations 11 and 12 can be combined and solved for an equivalent K_s, where $K_s = ET_{c\,adj}/ET_c$:

$$K_s = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{\text{e threshold}}\right)\text{..}(13)$$

for conditions when $EC_e > EC_{e\,\text{threshold}}$ and soil water depletion is less than the readily available soil water depth ($D_r < RAW$). D_r and RAW are defined in the previous section.

With water stress(D_r > RAW)

When soil water stress occurs in addition to salinity stress, Equations 6, 12 and 13 are combined to yield :

$$K_s = \left(1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\,threshold}\right)\right)\left(\frac{TAW - D_r}{TAW - RAW}\right)\text{..............................}(14)$$

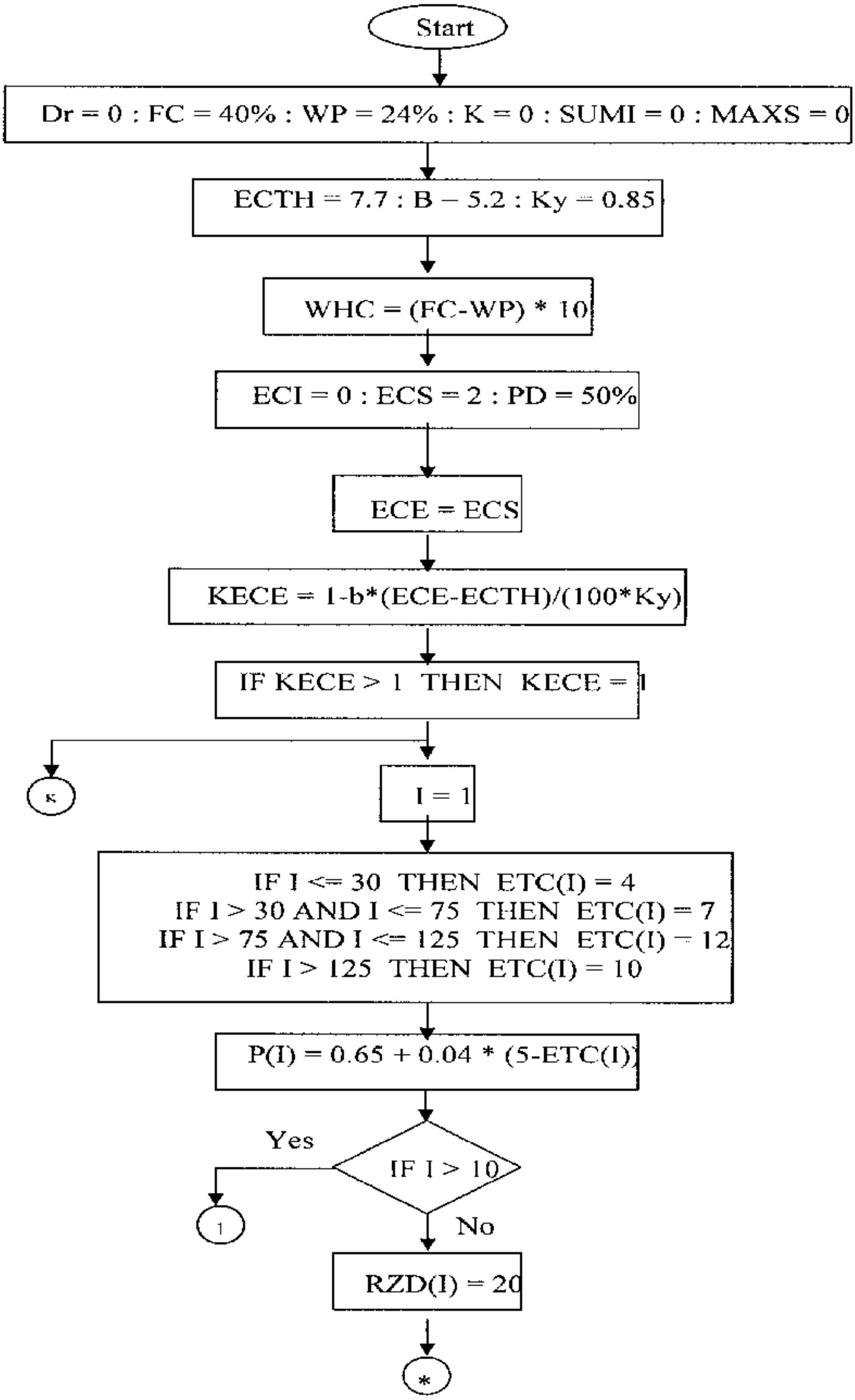
for conditions when $EC_e > EC_{e\ threshold}$ and $D_r > RAW$.

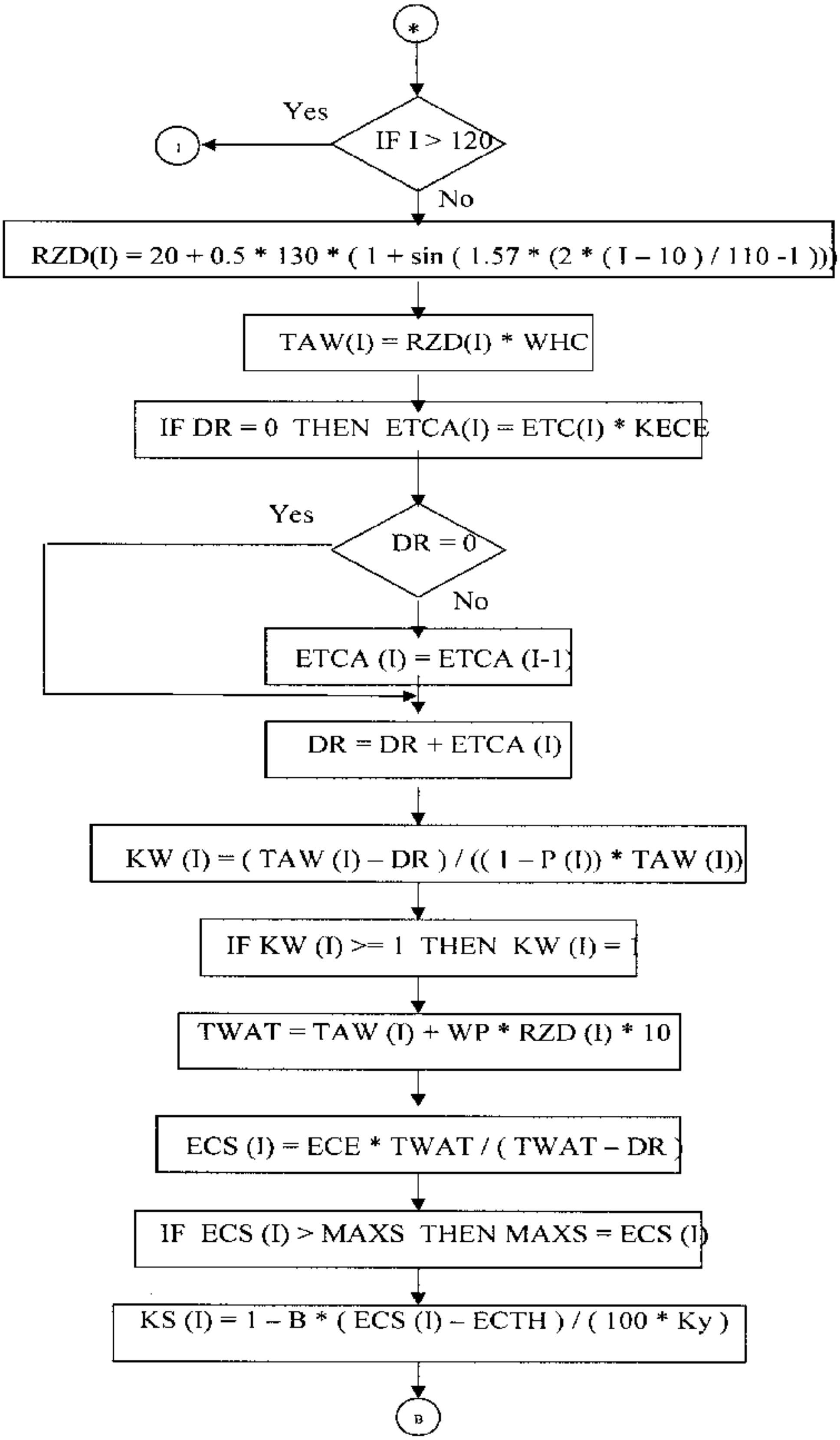
Figure 1 shows the flowchart of the main components of the simulation model.

Model Application and Discussion of Results

The proposed model is applied using climatic and soil data for a site at northern Syria with cotton summer crop. The initial soil salinity at the beginning of the irrigation season, which is April 20, was 2 dS/m. Different values for the irrigation water salinity (0, 1, 2, 3, 4, 5 dS/m) are tested. Furthermore, different levels of soil moisture depletion, ranging between 30% and 90%, are tried (MAAR, 2005). For cotton crop, the value of p in equation (4) is 0.65. Also, the values of $EC_{e\ threshold}$ and b in equation (11) are 7.7 dS/m and 5.2 , respectively. For the yield and evapotranspiration relationship in equation (12), a seasonal K_y value is adopted which was equal to (0.85) (Table 24 FAO,1998). The length of the growing season for cotton in the selected site is around 180 days, therefore, last irrigation should be given before October,20. Measured values for ET_o , using Neutron probe devices, are used in equation (1). For the crop coefficient, K_c, the single crop coefficient is used as described by the FAO(1998).

Figure 2 shows typical results for salinity build up in the soil profile during the growing


Start
Dr = 0 : FC = 40% : WP = 24% : K = 0 : SUMI = 0 : MAXS = 0
ECTH = 7.7 : B = 5.2 : Ky = 0.85
WHC = (FC-WP) * 10
ECI = 0 : ECS = 2 : PD = 50%
ECE = ECS
KECE = 1-b*(ECE-ECTH)/(100*Ky)
IF KECE > 1 THEN KECE = 1
K
I = 1
IF I <= 30 THEN ETC(I) = 4
IF I > 30 AND I <= 75 THEN ETC(I) = 7
IF I > 75 AND I <= 125 THEN ETC(I) = 12
IF I > 125 THEN ETC(I) = 10
P(I) = 0.65 + 0.04 * (5-ETC(I))
Yes
IF I > 10
1
No
RZD(I) = 20
*


*
Yes
1
IF I > 120
No
RZD(I) = 20 + 0.5 * 130 * (1 + sin (1.57 * (2 * (I – 10) / 110 -1)))
TAW(I) = RZD(I) * WHC
IF DR = 0 THEN ETCA(I) = ETC(I) * KECE
Yes
DR = 0
No
ETCA (I) = ETCA (I-1)
DR = DR + ETCA (I)
KW (I) = (TAW (I) – DR) / ((1 – P (I)) * TAW (I))
IF KW (I) >= 1 THEN KW (I) = 1
TWAT = TAW (I) + WP * RZD (I) * 10
ECS (I) = ECE * TWAT / (TWAT – DR)
IF ECS (I) > MAXS THEN MAXS = ECS (I)
KS (I) = 1 – B * (ECS (I) – ECTH) / (100 * Ky)
B

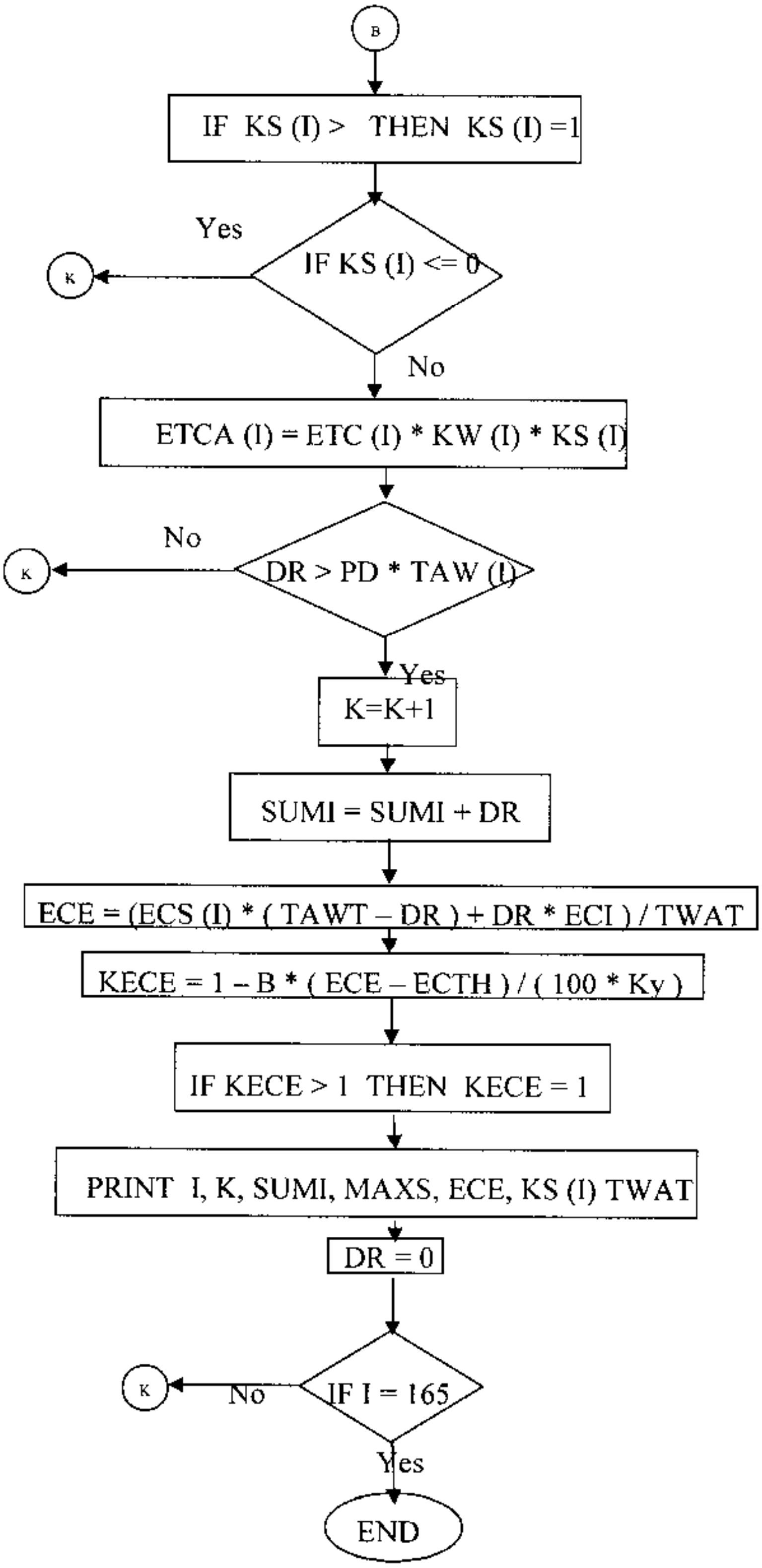
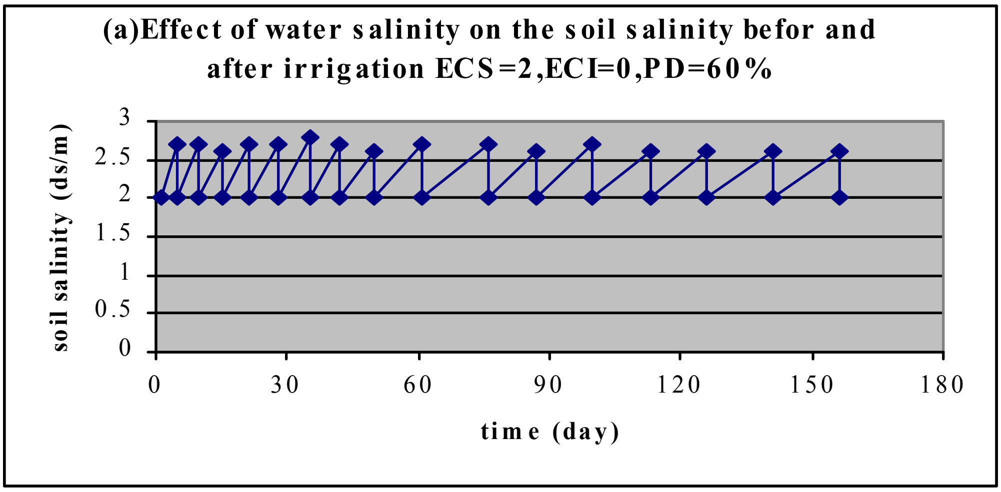
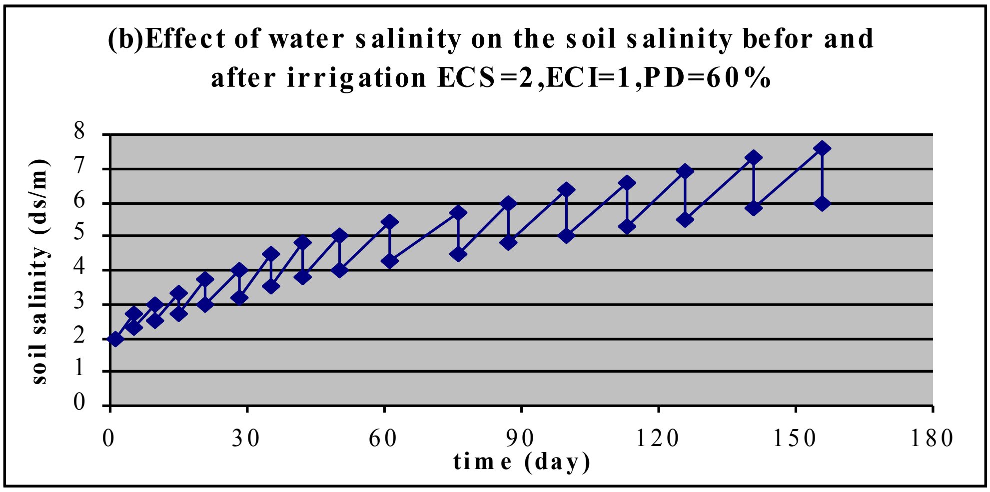


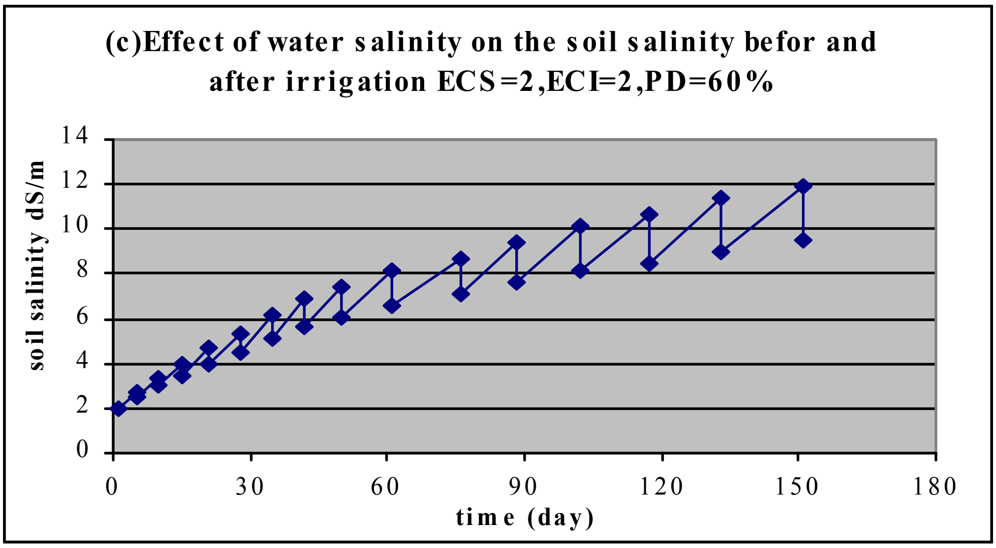
Figure 1 flowchart of the main components of the simulation model.



(a)Effect of water salinity on the soil salinity befor and after irrigation ECS=2,ECI=0,PD=60%



(b)Effect of water salinity on the soil salinity befor and after irrigation ECS=2,ECI=1,PD=60%



(c)Effect of water salinity on the soil salinity befor and after irrigation ECS=2,ECI=2,PD=60%

Figure 2 Typical output of the simulation model for different salinity of irrigation water. Initial EC of soil = 2 dS/m.

season. Table (1) presents a summary of the results for different simulation runs using different combinations of *EC* irrigation water and percent allowable soil moisture depletion. A careful examination of the model output in Table (1) reveals the followings:

a. since *P* for cotton is equal to 0.65, there is no soil water stress on the crop for the cases of 30, 40, 50 and 60%. The only stress that may affect the crop for these cases is due to salinity built- up when it exceeds 7.7 dS/m .
b. for the same percent depletion but different *EC* of irrigation water, the same seasonal ET_{cadj} is obtained if the soil *EC* dose not exceed 7.7 dS/m during the growing season. This can be clearly seen for the cases of 80% and 90% depletion.

   For the case of 90% depletion as an example, the sum seasonal ET_c adjusted (456mm) is obtained for the *EC* of irrigation of 0,1,2,3,and 4 dS/m because the *EC* of soil did not reach the critical (threshold) limit of 7.7 dS/m during the growing season.
c. Soil salinity build up during growing season under deficit irrigation (with no leaching) reduces the water up take by the plant. Consequently, both the seasonal ET_{cadj} and number of irrigation decreases although there is no water shortage or water stress in the root zone. This can be clearly seen for all cases of percent depletion that are less than *p* (i.e 65% for cotton).

d. although there is no stress due to neither soil water nor to salinity during the entire growing season for runs No 1, 2, 7, 8, 13, 14, 19 and 20, the seasonal ET_c differ because of different day of last irrigation. Day of last irrigation is defined as the day in which irrigation water applied is enough to maintain soil water content in the root zone above the assigned level of percent depletion. The seasonal ET value for these eight cases ranges between 746 mm and 877 mm.

Of course, the relative crop yield for these eight runs is equal to 1, because the crop has not been subjected to any stress, neither soil water no salinity. This is because P<= 65% and EC during the growing season <= 7.7 dS/m.

e. If it is desired that soil salinity build up during the growing season not to exceed the threshold ECe (that is 7.7 dS/m for cotton) some amount of leaching should

Table (1) Results of model application for different % Depletion and EC of irrigation water with initial EC of soil = 2 dS/m. Planting date April, 20.

Run No.	Day of last Irrigation	No of Irrigations	*EC* of Irrigation Water	Percent Depletion	Seasonal ET_c mm	*EC* of soil after last Irrigation dS/m
1	152	20	0	30	841	2.0
2	152	20	1	30	841	5.1
3	152	20	2	30	841	7.8
4	159	20	3	30	835	10.5
5	161	19	4	30	774	12.8
6	162	18	5	30	707	14.7
7	153	15	0	40	845	2.0
8	153	15	1	40	845	5.2
9	153	15	2	40	845	8.0
10	161	15	3	40	841	10.8
11	149	14	4	40	742	12.8
12	140	13	5	40	653	14.3
13	161	12	0	50	877	2.0
14	161	12	1	50	877	5.4
15	161	12	2	50	876	8.3
16	132	11	3	50	741	10.3
17	157	11	4	50	764	13.1
18	134	10	5	50	640	14.3
19	131	9	0	60	746	2.7
20	131	9	1	60	746	5.3
21	131	9	2	60	746	8.0
22	134	9	3	60	738	10.5
23	153	9	4	60	743	13.2
24	125	8	5	60	604	14.2
25	151	8	0	70	798	2.0
26	151	8	1	70	798	5.6
27	151	8	2	70	797	8.4
28	158	8	3	70	795	11.2
29	126	7	4	70	632	12.4
30	143	7	5	70	640	14.7
31	134	6	0	80	666	2.0
32	134	6	1	80	666	5.3
33	134	6	2	80	666	7.7

34	136	6	3	80	664	10.1
35	149	6	4	80	670	12.4
36	116	5	5	80	486	12.4
37	145	3	0	90	456	3.1
38	145	3	1	90	456	4.3
39	145	3	2	90	456	5.4
40	145	3	3	90	456	6.5
41	145	3	4	90	456	7.7
42	146	3	5	90	455.6	8.8

Table (2) Relative yield and relative seasonal ET_{cadj} for different % depletion initial soil salinity of the profile = 2 dS/m

Percent Depletion	Run No.	ET_{cadj}/ET_c	Y_a/Y_m
30	1	1	1
30	2	1	1
30	3	1	1
30	4	0.99	1
30	5	0.92	0.99
30	6	0.84	0.93
40	7	1	0.86
40	8	1	1
40	9	1	1
40	10	0.99	0.99
40	11	0.88	0.90
40	12	0.77	0.81
50	13	1	1
50	14	1	1
50	15	1	1
50	16	0.84	0.86
50	17	0.87	0.89
50	18	0.73	0.77
60	19	1	1
60	20	1	1
60	21	1	1

60	22	0.99	0.99
60	23	0.99	0.99
60	24	0.81	0.84
70	25	1	1
70	26	1	1
70	27	1	1
70	28	0.99	0.99
70	29	0.79	0.82
70	30	0.8	0.83
80	31	1	1
80	32	1	1
80	33	1	1
80	34	1	1
80	35	1	1
80	36	0.73	0.77
90	37	1	1
90	38	1	1
90	39	1	1
90	40	1	1
90	41	1	1
90	42	1	1

be incorporated with the irrigation water. In this case, the total seasonal ET will not drop below the maximum (and yield will stay at maximum) for the percent depletion of 30, 40, 50, and 60%.

f. If water use efficiency (WUE) is defined as crop yield divided by seasonal ET, runs No 19 and 20 give the highest WUE. In other words, the management alternative of irrigation at 60% with EC of zero and 1 dS/m has resulted in maximum WUE.

g. Number of irrigations is an important factor in the design, operation and management of farm irrigation systems. The results in Table (1) show that number of irrigations greatly decrease with increasing of % soil moisture depletion. As number of irrigation decreases, cost of operating the system decreases, but this may adversely affect the profit (net economical return) due to lowering the yield of crop.

Deficit irrigation and yield

Table 2 presents the relative yield for all runs in Table 1. Each group of percent depletion is treated separately with respect to ET_c , upon which the relative seasonal ET is calculated. The relative yield Y_a/Y_m for cotton is calculated by equation (12) using a seasonal K_y value of 0.85. For example, the relative seasonal ET_c is equal to 1 for runs No. 1, 2, 7, 8, 13, 14, 19 and 20 , although the absolute seasonal ET_c are different. Figure 3 shows the variation of relative yield Y_a/Y_m with the relative seasonal evapotranspiration.

Fig 3 presents the relation between relative yield Y_a/Y_m with the relative seasonal evapotranspiration ET_{cadj}/ET_c for cotton crop in the following form:

$$Y_a/Y_m = (ET_{cadj}/ET_c)^{0.83} \dots\dots\dots\dots\dots\dots \quad (15)$$

Figure 3 and Eq. (15) are useful in the management of deficit irrigation. They demonstrate how to incorporate the effect of stress due to salinity with the stress due to water on the final crop yield. Given the salinity of irrigation water and selecting a certin level of deficit irrigation, the relative evapotranspiration (Et_{cadj}/ET_c) can be predicted. Upon knowing the relative evapotranspiration, the relative yield under the given conditions can be also evaluated.

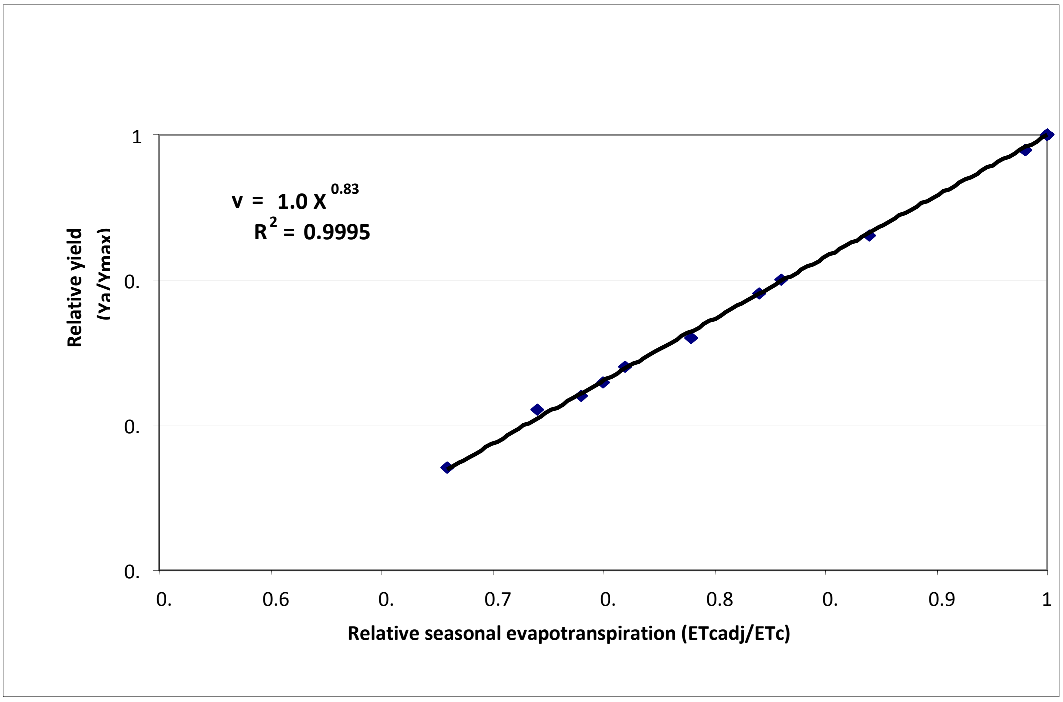


Figure 3. Relation between relative yield (Y_a/Y_{max}) and relative seasonal

evapotranspiration (ET_{cadj}/ET_c)

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