Chapter 4: Systems approach to water productivity assessment using cropping system Models

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4.1 Background and justification

Irrigation management of crops in Egypt is characterized by the application of more water than the crops require. In fact, large amounts of water are supplied without any estimates of the soil water content at the root zone. The rationale for doing so is the assumption that more irrigation water means a greater yield. So, eliminating the use of this unnecessary irrigation water could help save the resource, provided that this can be done with low yield losses. The estimation of soil water reserves in the root zone area is essential for the best irrigation management. This management can be done by modeling water depletion from the root zone under the application of different amounts of irrigation water (Khalil et al., 2007). Models that simulate crop growth and water flow in the root zone can be powerful tools for extrapolating findings and conclusions from field studies to conditions not tested (Smith et al., 2000). Therefore, using these types of models to predict the effect of applying deficit irrigation on the yield of several crops could be an ultimate solution to conserving irrigation water.

Deficit irrigation, while it may result in a yield reduction, in general increases water productivity and has the added benefit that the irrigation water saved can be used in new lands. However, testing these deficit irrigation practices in the field is expensive. Therefore, simulation models could partially substitute for experiments to test different deficit irrigation scenarios and be used to develop recommendations for the conservation of irrigation water and the minimizing of yield losses. Three models were selected for that purpose, CROPWAT, Yield-Stress and CropSyst. Our objective was to use these models to assess the effects of different deficit irrigation scenarios on the yields of crops planted in the field trials.

4.2 Application of the CROPWAT model

CROPWAT was developed by the FAO Land and Water Development Division (FAO, 1992). It includes a simple water balance model that allows the simulation of crop deficit irrigation conditions and estimation of yield reductions based on well established methodologies for determining crop evapotranspiration and yield responses to water (FAO, 1979). The CROPWAT model can adequately simulate yield reduction as a result of imposed deficit irrigation. It accounts well for the relative sensitivity of different growth stages and it is able to reproduce the negative impact of deficit irrigation on yield.

4.2.1. Methodology

CROPWAT (version 4.3) is a computer program based on the FAO (1992) Penman-Monteith combination method for calculating reference crop evapotranspiration (ETo) values. These estimates are used in crop water requirement and irrigation scheduling calculations.

The FAO Penman-Monteith method can be expressed as (Allen et al. 1998):

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2\,(es\text{-}ea)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

Where:
ET_o is the reference evapotranspiration (mm day^{-1})
R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1})
G is the soil heat flux density (MJ m^{-2} day^{-1})
T is the mean daily air temperature at 2 m height (°C)
u_2 is the wind speed at 2 m height (m s^{-1})
es is the saturation vapor pressure (kPa)
ea is the actual vapor pressure (kPa)
es-ea is the vapor pressure deficit (kPa)
Δ is the slope of the vapor pressure-temperature curve (kPa °C^{-1})
γ is a psychometric constant (kPa °C^{-1})

Crop water requirements (ET_{crop}) over the growing season are determined from ET_o and estimates of crop evaporation rates, expressed as a crop coefficient, (K_c) according to the following equation:

$$\text{Crop water requirement } (ET_{crop}) = ET_o * K_c$$

The effect of water stress on yield is quantified by relating the relative yield decrease to the relative evapotranspiration deficit by an empirically derived yield response factor (K_y) expressed as:

$$K_y = \frac{(1 - \frac{Y_a}{Y_m})}{(1 - \frac{ET_a}{ET_m})}$$

Where:
Y_a is the actual yield
Y_m is the maximum yield
ET_a is the actual evapotranspiration
ET_m is the maximum evapotranspiration

The model was calibrated using weather, soil, and crop data for El-Bustan area. The effect of different irrigation scheduling scenarios and sowing dates on crop water requirements and crop productivity were tested for three crops – wheat, maize, and peanuts. Wheat was planted under sprinkler irrigation (5 day irrigation interval) where five sowing dates were tested, October 15, November 1, November 15, December 1, and December 15. The irrigation scheduling scenarios for wheat are presented in Table 4.1.

Maize was grown under drip irrigation (2 days irrigation interval). The tested sowing dates were: May 1, May 15, June 1, June 15, July 1, and July 15. Table 4.2 and Table 4.3 show the irrigation scheduling scenarios for maize and peanut, respectively.

The model was validated using measured field data for the wheat crop during the 2005-2006 winter season at two sites, El-Bustan, representing the new lands, and

Table 4.1. Irrigation scheduling scenarios for wheat.

Irrigation scheduling scenario	Growth stage			
	Net irrigation requirements (%)			
	Initial (I)	Develop. (II)	Mid. (III)	Late (IV)
1	100	100	100	100
2	75	75	75	75
3	50	50	50	50
4	50	75	100	100
5	50	100	100	50

Table 4.2. Irrigation scheduling scenarios for maize.

Irrigation scheduling scenario	Growth stage			
	Net irrigation requirements (%)			
	Initial (I)	Develop. (II)	Mid. (III)	Late (IV)
1	100	100	100	100
2	75	75	75	75
3	75	75	100	75
4	75	100	100	75
5	50	50	50	50
6	50	100	100	50
7	50	75	100	50
8	50	75	100	75

Table 4.3. Irrigation scheduling scenarios for peanut.

Irrigation scheduling scenario	Growth stage			
	Net irrigation requirements (%)			
	Initial (I)	Develop. (II)	Mid. (III)	Late (IV)
1	100	100	100	100
2	75	75	75	75
3	75	100	100	75
4	50	50	50	50
5	50	100	100	50

Monofia, representing the old lands. Four farms in the old lands and three farms in the new lands were selected for the on-farm trials on the wheat crop and the appropriate interventions suitable for each site were applied.

For the wheat planted in El-Monofia, four irrigation treatments were used. These were

1. Full irrigation (ET + 0.2 ET as a leaching requirement – I_{FULL}) under researcher supervision
2. Deficit irrigation (irrigation with 70% of full irrigation – $I_{0.7FULL}$) under researcher supervision
3. Wide furrow irrigation (done by combining two furrows and five wheat rows sown on each wide furrow) which was compared to the traditional separate furrows (two rows sown on each furrow), ($I_{W\text{-}FURROW}$), irrigated by the farmers with the amount of water applied being measured by the researcher, and
4. The farmers' irrigation treatment, (I_{FARMER}). Irrigation by the farmer with the amount of water applied being measured by the researcher.

At El-Bustan, three irrigation treatments were proposed

1. Full irrigation (ET + 0.2 ET as leaching requirement, I_{FULL}) under researcher supervision
2. Deficit irrigation (irrigation with 80% of

full irrigation, $I_{0.8FULL}$) under researcher supervision, and

3. Farmers' irrigation treatment, (I_{FARMER}); irrigation by the farmer with the amount of water applied being measured by the researcher.

Weather data, crop data, and soil data are included in Annex 1.

4.2.2. Results and Discussion

Calibration of the model has been done both for sowing date and irrigation scheduling.

The effect of the sowing date on the water requirements of wheat, peanut, and maize crops at El-Bustan area is presented in Table 4.4. For the wheat crop, the results indicate that crop water requirements (ET_{crop}) increased from 245.3 mm to 356.0 mm as the sowing date progressed from October 15 to December 15. Also, the net irrigation requirements increased from 241.2 mm to 349.0 mm for the respective sowing dates.

Comparing the changes in water requirements and expected yields with the same values for the optimum sowing date, Nov. 15, showed that the water requirements were -13.08% for the October 15 sowing date, -8.04% for the November 1 sowing, +12.69% for the December 1 sowing, and +26.15% for the December 15 sowing. The corresponding changes in yields were -20%, -5%, 0%, and -15% for these sowing dates.

From the results obtained, it could be concluded that wheat could be sown in El-Bustan area during the first half of November with a saving of about 8% in

Table 4.4. Effect of sowing dates on wheat, peanut, and maize crop water requirements.

Crop	Sowing date	ET_{crop} (mm)	Net irrigation (mm)	Yield expected (%)	ET change (%)	Yield change (%)
Wheat	Oct 15	245.30	241.20	80.00	-13.08	-20.00
	Nov 1	259.50	254.70	95.00	-8.04	-5.00
	Nov 15	282.20	276.80	100.00	0.00	0.00
	Dec 1	318.00	312.00	100.00	12.69	0.00
	Dec 15	356.00	349.00	85.00	26.15	-15.00
Peanut	Apr 1	520.80	507.20	95.00	-4.00	-5.00
	Apr 15	535.60	522.40	100.00	-1.27	0.00
	May 1	542.50	530.10	100.00	0.00	0.00
	May 15	539.60	528.20	90.00	-0.53	-10.00
	Jun 1	524.90	514.80	80.00	-3.24	-20.00
Maize	May 1	523.60	521.10	100.00	2.93	0.00
	May 15	508.70	506.40	100.00	0.00	0.00
	Jun 1	499.20	497.30	90.00	-1.87	-10.00
	Jun 15	465.00	463.20	80.00	-8.59	-20.00
	Jun 25	466.20	464.70	75.00	-8.35	-25.00
	Jul 1	429.36	427.80	70.00	-15.60	-30.00
	Jul 15	393.32	392.00	60.00	-22.68	-40.00

the irrigation water required; the resulting reduction in yield would be about 5%.

For the peanut crop, the results indicate that the highest ETc value of 542.5 mm was obtained for the optimum sowing date, May 1. They show also that, delaying the sowing dates to May 15 and June 1 resulted in 10% and 20% yield reductions. From the results obtained, it could be concluded that the best sowing time for a peanut crop in El-Bustan area is the period from April 15 to May 1. Peanut crops sown in this period were not subject to any yield reductions.

The data also show that the earliest (April 1) as well as the latest (June 1) sowings are not to be recommended. No appreciable water savings were achieved for sowings on either of these dates. Indeed, sowings on both dates negatively affected the yield. By delaying sowing until June 1, the yield was 20% lower than that recorded for the optimum sowing date.

For the maize crop, sowings on the optimal dates (May 1 and May 15) were accompanied by the highest crop water requirement values of 523.6 mm (May 1) and 508.7 mm (May 15). The results also show that the yield reduction for maize was increased from 10% to 40% with delays in the sowing date between June1 and July 15. Also, the ETcrop values were from 2% to 23% less than those for the optimum sowing dates. From the results obtained it could be concluded that the sowing date had a greater effect on the yield obtained than on the water requirements.

Data presented in Table 4.4 also show that the gradual delay in the sowing time resulted in a gradual reduction in the yield produced as well as in the ETcrop values. However, its negative effect was much more evident on the yield than on the maize water requirements.

In the El-Bustan area, where water is a limiting factor for agricultural production, the question to be answered is, "Is saving 20% in the amount of water applied, with the associated 40% reduction in yield resulting from delaying sowing until July 15, a sustainable way to meet the water shortage?" To answer the question, the crop water productivity needed to be measured.

The effects of different irrigation scheduling scenarios on the irrigation requirements and yields of wheat, peanut, and maize crops in El-Bustan area are presented in Tables 4.5, 4.6, and 4.7. For the wheat crop, (Table 4.5), the results show that irrigating with amounts of water equal to 75% and 50% of the actual crop water requirements for the whole season resulted in 12.6% and 35.6% yield reductions and 26.22% and 50.7% savings in irrigation water. The results also revealed that irrigating wheat with amounts of water equal to 50%, 75%, and 100% of the required water during the initial, development, mid-, and late-season growth stages, respectively, resulted in a 4.0% yield decrease and a 17.25% saving in irrigation water. Also, irrigating with 50% of the required water during the initial and

Table 4.5. Effect of irrigation scenarios on wheat yield and water requirements.

Wheat crop irrigation scenario	ET_c (mm)	Net irrigation (mm)	Predicted yield reduction (%)	Water saved (mm)	Water saved (%)
1) 100% at all stages	282.18	276.80	0.000	5.38	1.91
2) 75% at all stages	246.80	208.20	12.600	73.98	26.22
3) 50% at all stages	181.80	139.10	35.600	143.08	50.71
4) 50/75/100/100	270.90	233.50	4.000	48.68	17.25
5) 50% at stages I and IV	270.50	228.00	4.100	54.18	19.20

Table 4.6. Effect of irrigation scenarios on peanut yield and water requirements.

Peanut crop irrigation scenario	ET_c (mm)	Net irrigation (mm)	Predicted yield reduction (%)	Water saved (mm)	Water saved (%)
1) 100% at all stages	543	530	1.000	20.49	0.00
2) 75% at all stages	430	398	15.300	152.79	27.75
3) 75% at stages I and IV	523	491	3.500	59.59	10.82
4) 50% at all stages	302	264	31.600	286.29	52.00
5) 50% at stages I and IV	490	452	7.700	98.59	17.91

Table 4.7. Effect of irrigation scenarios on maize yield and water requirements.

Maize crop irrigation scenario	ET_c (mm)	Net irrigation (mm)	Predicted yield reduction (%)	Water saved (mm)	Water saved (%)
1) 100% all stages	508.70	506.40	0.00	2.30	0.45
2) 50% all stages	294.00	248.50	52.70	260.20	51.15
3) 50% stages I and IV	490.10	444.70	4.60	64.00	12.58
4) 75% all stages	417.20	372.80	22.50	135.90	26.72
5) 75% stages I and IV	508.70	470.40	0.00	38.30	7.53
6) 75% stages I, II, and IV	469.80	426.10	9.50	82.60	16.24
7) 50/75/100/50	446.00	400.50	15.40	108.20	21.27
8) 50/75/100/75	459.50	415.70	12.10	93.00	18.28

late-season growth stages resulted in a 4.1% yield reduction and a 19.2% saving in irrigation water.

Comparing the different irrigation scenarios concerning, on the one hand, the changes in yield and, on the other hand, the water saving percentages, it is quite evident that, in the case of a water shortage irrigation scheduling scenarios 4 and 5 should be followed, minimizing the yield reduction and saving more than 17% of the irrigation water.

For the peanut crop, (Table 4.6), irrigation with amounts of water equal to 75% and 50% of the crop water requirements resulted in 15.3% and 31.6% yield reductions and 27.75% and 52% savings in irrigation water. Irrigating the peanut crop with amounts of water equal to 75% of the requirement during the initial and late-season growth stages resulted in a 3.5% yield reduction and about an 11% saving in irrigation water. Irrigating with amounts of water equal to 50% of the required amount during the same growth stages resulted in a 7.7% yield reduction and about an 18% saving in water. Therefore, under conditions of limited available water resources and for areas suffering a water shortage, irrigating with amounts of water equal to 30% of that required during the initial and late season growth stages is the strategy to be recommended. The second best strategy to adopt for these conditions would be irrigating during the same growth stages with 75% of the peanut crop water requirements. Following both these irrigation scenarios, it is possible to minimize yield losses while at the same time maximizing water savings.

For the maize crop, (Table 4.7), irrigating with amounts of water equal to 75% and 50% of the crop water requirements for the whole season resulted in 22.5% and 52.7% reductions in maize yield and in 26.72% and 51.15% savings in irrigation water. Irrigating with amounts of water equal to 75% of the crop water requirements during the initial and late-season growth stages resulted in saving about 7.5% of the irrigation water without any reduction in yield. Irrigating with the same amounts of water during the initial, developing and late-season growth stages resulted in a 9.5% reduction in the yield and in saving about 16.24% in irrigation water. Also, irrigating with amounts of water equal to 50% of the crop water requirements during growth stages I and IV resulted in a 4.6% reduction in maize yield and a 12.6% saving in irrigation water. Under water shortage conditions, among the eight irrigation scenarios tested, the recommended ones are numbers three, five, and six for their superiority in minimizing yield reductions and improving water saving.

Old lands site (El-Monofia)

The measured field data and the predicted data for Monofia site are presented in Table 4.8. The results indicate that the actual amounts of irrigation water applied by the farmers for wheat were close to those calculated by the model. The results also indicate that there was close agreement between the actual (Yact) and predicted (Y_p) yields. The ratio (Y_p/Y_{act}) was not less than 0.984.

New lands site (El-Bustan)

The measured field data and the predicted data for El-Monofia site are presented in Table 4.8. The results indicate that the actual amounts of irrigation water applied by the farmers were less than those calculated by the model.

The results also show that there was close agreement between the actual (Y_{act}) and predicted (Y_p) yields. Table 4.9 summarizes the data for El-Bustan site. The trend of the experimental data is more or less similar to that at El-Monofia site. The ratio (Y_p/Y_{act}) varied between 0.87 (Sharab farmer and

Table 4.8. Measured and predicted data at the Monofia site, planting date Nov. 17 and seasonal effective rainfall 51 mm.

Name	ET_o (mm)	ET_m (mm)	Irr_{req} (mm)	EIW (mm)	Farmer irrigation treatment				Full irrigation treatment			
					ET_c (mm)	EIW_{act} (mm)	Y_{act} (t/ha)	Y_p (t/ha)	ET_c (mm)	EIW_{act} (mm)	Y_{act} (t/ha)	Y_p (t/ha)
Salam	392.9	313.5	262.4	524.8	308.5	534.0	9.440	9.289	308.5	526.7	8.000	7.872
Badr	395.2	315.9	264.9	529.7	313.5	557.1	7.607	7.554	313.5	550.5	8.321	8.263
Khatab	392.9	313.5	264.9	529.7	311.1	538.8	9.429	9.353	311.1	555.9	9.321	9.246
Maher	392.9	313.5	262.4	524.8	308.5	510.9	7.750	7.626	308.5	503.1	7.679	7.556
Salam	392.9	313.5	262.4	524.8	308.5	419.5	10.440	10.273	308.5	383.6	10.000	9.840
Badr	395.2	315.9	264.9	529.7	313.5	429.8	7.393	7.341	313.5	448.1	8.607	8.547
Khatab	392.9	313.5	264.9	529.7	311.1	435.5	9.464	9.388	311.1	400.2	8.964	8.892
Maher	392.9	313.5	262.4	524.8	308.5	396.0	6.646	6.540	308.5	350.2	8.393	8.259

Note: ET_o – reference crop evapotranspiration (FAO, P-M); $Rain_{eff}$ – effective rainfall; ET_m – non-stressed crop ET; ET_c – actual crop ET in the field; Irr_{req} – irrigation requirements (ET_m – $Rain_{eff}$); Y_{act} – actual yield EIW – estimated irrigation water requirement = [(Irr_{req}/ET_a) * LR]; LR – leaching requirements = 1.2; AIW_{act} – actual amount of applied irrigation water, Y_p – predicted yield.

Table 4.9. Measured and predicted data at El-Bustan site.

Name	Sowing date	ET_o (mm)	$Rain_{eff}$ (mm)	ET_m (mm)	Irr_{req} (mm)	AIW (mm)	Farmers' irrigation treatment				Full irrigation treatment				80% irrigation treatment			
							ET_c (mm)	AIW_{act} (mm)	Y_{act} (t/ha)	Y_p (t/ha)	ET_c (mm)	AIW_{act} (mm)	Y_{act} (t/ha)	Y_p (t/ha)	ET_c (mm)	AIW_{act} (mm)	Y_{act} (t/ha)	Y_p (t/ha)
Hala	Nov 21	421.3	15.0	336.7	321.7	454.2	331.7	412.0	5.786	5.699	315.2	411.4	6.750	6.318	307.1	335.9	6.110	5.572
Khalid	Nov 29	440.2	14.1	356.5	341.4	482.0	352.7	410.5	3.893	3.854	350.5	352.8	4.214	4.142	338.4	303.6	3.857	3.660
Sharab	Nov 23	425.7	15.1	341.4	326.3	453.6	325.8	408.6	3.929	3.748	315.1	367.8	3.750	3.461	297.5	300.0	3.714	3.235

80% irrigation treatment) and 0.99 (Khalid farmer and farmers' irrigation treatment).

Putting together the data summarized in Tables 4.8 and 4.9, it can be seen that the CROPWAT model can be used for irrigation scheduling and predicting the effect on crop yield and reductions in the amounts of irrigation water under both El-Bustan (new lands) and Monofia (old lands) conditions.

4.3 Yield-Stress model

The Yield-Stress model (Ouda, 2006) was developed, based on the same approach that CROPWAT uses. It estimates the amount of soil water reserved in the root zone area and determines crop evapotranspiration using a different method for the calculation of yield reduction as a result of deficit irrigation. Basically, the Yield-Stress model assumes that there is a linear relationship between available water and yield. Reduction in available water limits evapotranspiration and consequently reduces the yield. This assumption is supported by the previous work of several researchers (de Wit, 1958; Childs and Hanks, 1975; Bresler, 1987; Shani and Dudley, 2001).

The Yield-Stress model was designed to predict the effect of deficit irrigation scheduling on the yield of several crops and their consumptive water use (CWU). The model was used for the irrigation management of different crops under different stress conditions and its performance was acceptable.

4.3.1. Methodology

The main purpose of Yield-Stress model (Ouda 2006) is to predict crop yield under deficit irrigation for certain farms, based on the measured yield under no water stress. The Yield-Stress model uses a daily time step and requires two types of input data – input data by the user and an input data file. The model asks the user to input the planting and harvesting dates, the length of the growing season, crop yield, and soil characteristics – percent of clay, silt, sand, organic matter, and CaCO3.

The other input data source is a file representing the whole growing season, starting with the sowing month and date, and ending with the harvesting month and date. The file contains maximum, minimum, and mean temperatures, relative humidity, solar radiation, wind speed, the FAO's crop coefficient, and the date of and amount of water supplied at each irrigation. The model has three main components – the soil water balance calculation, salinity stress, and crop yield calculation routines.

The soil water balance is determined by calculating the readily available water at the root zone using equations described in FAO publication No 56 (FAO, 1998) as follows.

$TAW = (W_{FC}-W_{WP})\ Z$

$RAW = p\ TAW$

Where:
TAW is the total available water (mm)
W_{FC} is the water at field capacity (mm)
W_{WP} is the water at the wilting point (mm)
Z is the rooting depth (mm)
RAW is the readily available water (mm)
P is the soil water depletion fraction under no stress

The reference evapotranspiration (mm/day) was calculated using the Penman-Monteith equation (Allen et al., 1998) as follows:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T+273}\,u_2\,(es\text{-}ea)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

Where:
ET_o is the reference evapotranspiration (mm day^{-1})
R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1})
G is the soil heat flux density (MJ m^{-2} day^{-1})
T is the mean daily air temperature at 2 m height (°C)
u_2 is the wind speed at 2 m height (m s^{-1})
es is the saturation vapor pressure (kPa)
ea is the actual vapor pressure (kPa)

es-ea is the vapor pressure deficit (kPa)
Δ is the slope of the vapor pressure-temperature curve (kPa $^{o}C^{-1}$)
γ is a psychometric constant (kPa $^{o}C^{-1}$)

Crop evapotranspiration (ET_{crop}) is calculated by multiplying ET_o by the crop coefficient (K_c):

$$ET_{crop} = K_c\ ET_o$$

The model calculates the root zone depletion (D_r) by accumulating the ET_{crop} and comparing it on a daily basis with the readily available water. If the root zone depletion is higher than the readily available water, a deficit irrigation coefficient (K_s) is calculated and used to calculate an adjusted ET_{crop}, (ET_{cadj} mm day^{-1}) (FAO,. 1998).

$$K_s = (TAW-D_r)/((1-p)*TAW)$$

$$ET_{cadj} = K_s\ ET_{crop}$$

The salinity stress effect is calculated if the value of the irrigation water EC (EC_e) is higher than the EC threshold (EC_{es}). Under that condition, another water stress coefficient is calculated to combine the effect of water stress and salinity stress and a new value for ET_{cadj} is calculated (FAO, 1998).

$$K_{ss} = \left(1 - \frac{b}{K_y 100}(EC_e - EC_{es})\left(\frac{TAW - D_r}{(1-p)TAW}\right)\right)$$

Where:
b is the percent reduction in crop yield per unit dS m^{-1} increase in EC_e beyond the EC_e threshold
K_y is the yield response factor
EC_e is the electrical conductivity of a soil water solution after the addition of a sufficient quantity of distilled water to bring the soil water content to saturation.
EC_{es} is the EC of the saturation extract at the threshold of EC_e when the crop yield is reduced.

The old version of the model calculated crop yield on a daily basis as a function of water consumption. The model calculated a value for the accumulated yield per day throughout the growing season (Y_{mean}) by dividing the measured yield at the farm level ($Y_{measured}$) by the measured season length (SL):

$$Y_{mean} = Y_{measured}/SL$$

However, the model was modified to calculate dry matter production using the solar energy level as the limiting factor (Loomis and Williams, 1963). This method converts total solar radiation to micro-Einstein (μE). Then, it assumes that 82% of the visible light is intercepted by chloroplasts with a maximum quantum efficiency of 10% (10 photons reduce one CO_2 molecule). Furthermore, the method subtracts 33% of the gross photosynthesis as a respiration cost to calculate the net photosynthesis, which is converted from μmoles cm^{-2} to g m^{-2} dry matter produced per day.

The model accounts for water stress when the predicted readily available water is greater than the predicted ET_{crop}. If the predicted readily available water is lower than the predicted ET_{crop}, K_s will be less than 1 and the value of the predicted yield ($Y_{predicted}$) will be reduced in relation to the reduction in daily water consumption as follows:

$$Y_{predicted} = K_s\ Y_{predicted}$$

The Yield-Stress model was calibrated using crop data from the Resource Management Program of ARC, Egypt, in collaboration with ICARDA (long-term trials). The model was used to predict the yield and CWU of the six crops as indicated below under actual irrigation amounts and under four proposed deficit irrigation treatments:

- Cotton – data from six growing seasons were available for two sites, Beni Sweif and Damietta.
- Clover, soybeans, and wheat – data from four growing seasons were available for the Beni Sweif site.
- Onions and faba beans – data from three growing seasons were available for the Beni Sweif site.

These six crops were irrigated with either fresh water or agricultural drainage water. The salinity level of the agricultural drainage water was low, which did not pose any salinity stress on the growing crops. The model is calibrated by adjusting the crop K_c, which allows the model to predict both yield and CWU accurately. The model's predictions were compared to the measured data and the percent reduction between the measured and predicted values for each growing season was calculated; in addition to two goodness of fit measurements – the root mean squared error (Jamieson et al., 1998) and the Willmott index of agreement (Willmott, 1981).

After calibrating the model, it was used to predict the yield and CWU for the six crops under study under deficit water applications. For cotton, several deficit irrigation scenarios were used, 80%, 70%, 60%, and 50% of the total amount of required irrigation water. For clover, faba bean, onions, and soybeans, amounts of irrigation water equal to 95%, 90%, 85%, and 80% of the crop CWU were applied. The model was used to predict the wheat yield and CWU under 90%, 85%, 80%, and 75% of total amount of the crop irrigation water requirements.

The model was validated using field data for wheat gathered during the 2005-2006 winter season at two sites, El-Monofia, representing the old lands, and Damietta, representing marginal lands (salt affected soil). Four farms on the old lands and six farms on the marginal lands were chosen. On the marginal lands, two farms used fresh water for irrigation, and two farms used either fresh or agricultural drainage water, depending on the availability of the fresh water in the misqa. The rest of the farms used agricultural drainage water for irrigation. Two irrigation treatments were used at the two sites to validate the model. On the old lands, two tests were conducted. The first allowed the farmers to use traditional irrigation practices and quantities of water while the second test used about 80% of the farmers' traditional volumes of water. On marginal lands, instead of 80%, about 75% of farmers' usual volumes of irrigation water were used. After validating the model, it was used to predict wheat yield and CWU for a 30% reduction of the total irrigation amounts at the two sites.

Two farms were chosen at El-Serw site where agricultural drainage water was used for irrigating wheat in the 2005-2006 growing season. These two farms were located at Kharg El-Zemam, where the soil is characterized by being saline-alkaline. Soil EC was 9.5 dS/m for Farm 1 and 6.8 dS/m for Farm 2. Wheat can tolerate salinity up to 6 dS/m, so salinity stress existed at both farms. The Yield-Stress model can simulate the effect of salinity stress on wheat yield, where a salinity stress coefficient (Kss) is calculated by the model and used to reduce the CWU and yield. Two irrigation treatments were used one involving the farmers' traditional irrigation volumes and the other using about 80% of these.

4.3.2 Results and discussion

The results, presented in Tables 4.10, 4.11, 4.12, 4.13, 4.14, and 4.15, showed clearly the accuracy of the model in predicting the yield of the six crops studied. That accuracy can be attributed to the method that the Yield-Stress model used in predicting yield under no water stress conditions. Similar results were obtained for soybean (Ouda et al., 2007 and Ouda et al., 2008c), wheat (Ouda 2006; El-Mesiry et al., 2007 and Ouda et al., 2008a) and sesame (Tantawy et al., 2007).

However, the model was less accurate in predicting CWU for some of the growing seasons (Tables 4.16, 4.17, 4.18, 4.19, 4.20, and 4.21), especially for cotton and onions. Similar results were obtained for maize (Ouda et al., 2007 and Ouda et al., 2008b) and barley (Khalil et al., 2007).

Table 4.10. Actual and predicted yield for cotton planted at Beni Sweif and El-Serw sites.

Location	Year	Fresh water irrigation			Drainage water irrigation		
		Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
		Actual	Predicted		Actual	Predicted	
Beni Sweif	1997	3.80	3.80	0	4.33	4.33	0
	1998	2.10	2.10	0	2.20	2.20	0
	2000	3.25	3.25	0	3.16	3.11	1.58
	2001	2.72	2.71	0.37	2.81	2.79	0.71
El-Serw	1999	3.12	3.12	0	3.36	3.35	0.30
	2002	1.71	1.71	0	2.07	2.07	0
RMSE	0.0002				0.0102		
Willmott index	0.9999				0.9999		

Note: RMSE – root mean square error

Table 4.11. Actual and predicted yield of clover planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1997-1998	5.29	5.21	1.51	4.97	4.83	2.82
1998-1999	7.88	7.88	0.00	8.74	8.74	0.00
1999-1000	7.66	7.59	0.91	7.51	7.48	0.40
2000-2001	7.55	7.43	1.59	7.88	7.75	1.65
RMSE	0.0188			0.0221		
Willmott index	0.9999			0.9999		

Note: RMSE – root mean square error

Table 4.12. Actual and predicted yield of soybeans planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998	1.21	1.20	0.83	1.34	1.33	0.75
1999	2.26	2.24	0.88	1.78	1.77	0.56
2000	1.73	1.70	1.73	1.56	1.54	1.28
2001	1.73	1.67	3.47	0.88	0.86	2.27
RMSE	0.0340			0.0189		
Willmott index	0.9998			0.9999		

Note: RMSE – root mean square error

Table 4.13. Actual and predicted yield of wheat planted at Beni Sweif under fresh water and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-1999	5.28	5.28	0	5.23	5.23	0
1999-2000	5.73	5.73	0	4.73	4.73	0
2000-2001	5.74	5.73	0.17	6.32	6.31	0.16
2001-2002	6.82	6.79	0.44	6.55	6.52	0.46
RMSE	0.0044			0.0046		
Willmott index	0.9999			0.9999		

Note: RMSE – root mean square error

Table 4.14. Actual and predicted yield of faba bean planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-1999	2.90	2.88	0.69	2.37	2.37	0
1999-2000	3.62	3.60	0.55	4.08	4.08	0
2001-2002	2.22	2.20	0.90	2.01	2.00	0.50
RMSE	0.0132			0.0039		
Willmott index	0.9999			0.9999		

Note: RMSE – root mean square error

Table 4.15. Actual and predicted yield of onions planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Yield (t/ha)		Reduction (%)	Yield (t/ha)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-1999	18.37	18.33	0.22	15.33	15.3	0.20
1999-2000	11.43	11.42	0.09	10.07	10.06	0.10
2001-2002	12.09	12.09	0	9.48	9.48	0
RMSE	0.0032			0.0030		
Willmott index	0.9999			0.9999		

Note: RMSE – root mean square error

Table 4.16. Actual and predicted CWU for cotton planted at two sites.

Location	Year	Fresh water irrigation			Drainage water irrigation		
		Water used (cm)		Reduction (%)	Water used (cm)		Reduction (%)
		Act.	Pred.		Act.	Pred.	
Beni Sweif	1997	52.02	54.61	4.98	59.41	54.61	8.08
	1998	69.57	67.42	3.09	71.10	67.40	5.20
	2000	68.62	68.46	0.23	73.93	68.84	6.88
	2001	72.93	74.49	2.14	74.38	74.61	0.31
El-Serw	1999	57.50	56.32	2.05	53.90	56.94	5.64
	2002	58.80	58.89	0.15	56.70	58.89	3.86
RMSE		0.0343			0.0780		
Willmott index		0.9998			0.9992		

Note: RMSE – root mean square error

Table 4.17. Actual and predicted CWU for clover planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Water used (cm)		Reduction (%)	Water used (cm)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1997-1998	22.30	22.82	2.33	22.94	22.68	1.13
1998-1999	20.53	20.46	0.34	20.78	20.46	1.54
1999-2000	26.01	26.35	1.31	26.17	26.36	0.73
2000-2001	26.35	27.72	5.20	26.36	27.72	5.16
RMSE	0.0527			0.0496		
Willmott index	0.9996			0.9997		

Note: RMSE – root mean square error.

Table 4.17. Actual and predicted CWU for clover planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	Water used (cm)		Reduction (%)	Water used (cm)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1997-1998	22.30	22.82	2.33	22.94	22.68	1.13
1998-1999	20.53	20.46	0.34	20.78	20.46	1.54
1999-2000	26.01	26.35	1.31	26.17	26.36	0.73
2000-2001	26.35	27.72	5.20	26.36	27.72	5.16
RMSE	0.0527			0.0496		
Willmott index	0.9996			0.9997		

Note: RMSE – root mean square error.

Table 4.18. Actual and predicted CWU for soybeans planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	CWU (cm)		Reduction (%)	CWU (cm)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998	34.67	33.40	3.66	35.68	34.72	2.69
1999	39.36	38.19	2.97	39.10	38.29	2.07
2000	37.26	36.75	1.37	37.90	36.83	2.82
2001	38.29	39.11	2.14	40.17	39.55	1.54
RMSE	0.0440			0.0384		
Willmott index	0.9998			0.9998		

Note: RMSE – root mean square error.

Table 4.19. Actual and predicted CWU for wheat planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	CWU (cm)		Reduction (%)	CWU (cm)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-99	40.04	41.03	2.47	40.72	41.03	0.76
1999-00	41.28	41.88	1.45	42.64	41.88	1.78
2000-01	44.73	44.32	0.92	45.63	44.32	2.87
2001-02	44.90	45.84	2.09	46.66	45.84	1.76
RMSE	0.0301			0.0332		
Willmott index	0.9999			0.9998		

Note: RMSE – root mean square error.

Table 4.20. Actual and predicted CWU for faba bean planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	CWU (cm)		Reduction (%)	CWU (cm)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-1999	30.93	30.71	0.71	31.69	31.63	0.19
1999-2000	33.94	33.36	1.71	35.46	33.57	5.33
2001-2002	35.45	34.62	2.34	35.61	34.67	2.64
RMSE	0.0344			0.0685		
Willmott index	0.9999			0.9996		

Note: RMSE – root mean square error.

Table 4.21. Actual and predicted CWU for onions planted at Beni Sweif under fresh and drainage water irrigation.

Season	Fresh water irrigation			Drainage water irrigation		
	CWU (m^3)		Reduction (%)	CWU (m^3)		Reduction (%)
	Actual	Predicted		Actual	Predicted	
1998-1999	20.66	20.41	1.21	21.16	20.49	3.17
1999-2000	20.92	20.34	2.77	21.32	20.44	4.13
2001-2002	21.46	21.03	2.00	22.06	21.13	4.22
RMSE	0.4040			0.0746		
Willmott index	0.9998			0.9994		

Note: RMSE – root mean square error.

4.3.3 Tested scenarios of deficit irrigation

Cotton yield

Predicted cotton yield under deficit irrigation - Beni Sweif site

The data representing the predicted yield (t/ha) and the percent reductions in yield under the different irrigation treatments using both fresh and drainage water are given in Table 4.22. The data presented show clearly that under deficit irrigation, gradual reduction in the volumes of water applied (up to 50%) did not result in any significant differences in the predicted yield (the reduction was less than 2%).

This was also the case in the 1998 growing season (Table 4.22). The data show that up to 30% of the total irrigation water could be saved with concomitant yield losses of less than 2% under both fresh and drainage water irrigation.

In the 2000 growing season (Table 4.22), the data show that irrigating with a volume of water not less than 70% of the full irrigation requirement did not result in any significant reduction in the predicted yield – it being 2% lower than that under full irrigation. However, reducing the volume of water applied water to 60% and 50% of the full irrigation requirement resulted in a drastic drop in yield – losses of 11% and 26% being observed. From the data for the 2000 growing season it can be seen that there is a high potential for water saving (corresponding to nearly 30% of the full irrigation amount) with associated yield losses not exceeding 2%.

Likewise for the 2001 growing season (Table 4.22), for both irrigation water sources, nearly 40% of the water applied under the full irrigation treatment could be saved with an associated reduction in the cotton yield of around 3%.

Predicted cotton yield under deficit irrigation – El-Serw site

For cotton planted at El-Serw in the 1999 growing season (Table 4.23), the yield responded to deficit irrigation treatments in a manner completely different from that obtained at the Beni Sweif site.

The data reveal that under deficit irrigation, the lower the volume of water applied, the higher is the reduction in the predicted yield. Under irrigation with a volume of water amounting to 50% of the full requirement, the yield was seriously affected, with losses reaching 60% of that obtained under the full irrigation with fresh and/or drainage water. Reducing the amount of water applied to 80% of the full irrigation requirement also affected the predicted yield, but at a relatively lower amount – just 7% of that under full irrigation. This means that reducing the volume of water applied by more than

Table 4.22. Predicted cotton yield and its percent reduction under different deficit irrigation treatments using fresh and drainage irrigation water in four successive growing seasons 1998-2001 at Beni Sweif site.

Growing season 1997

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	3.80	0	4.33	0
80% of total irrigation	3.80	0	4.33	0
70% of total irrigation	3.80	0	4.33	0
60% of total irrigation	3.79	0.26	4.32	0.23
50% of total irrigation	3.73	1.84	4.29	0.92

Growing season 1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	2.10	0	2.20	0
80% of total irrigation	2.07	1.43	2.19	0.45
70% of total irrigation	2.06	1.90	2.17	1.36
60% of total irrigation	1.86	11.43	2.04	7.27
50% of total irrigation	1.55	26.19	1.75	20.45

Growing season 2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	3.25	0	3.11	0
80% of total irrigation	3.19	1.85	3.08	0.96
70% of total irrigation	3.01	7.38	2.92	6.11
60% of total irrigation	2.75	15.38	2.68	13.83
50% of total irrigation	2.41	25.85	2.34	24.76

Growing season 2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	2.71	0	2.79	0
80% of total irrigation	2.71	0	2.79	0
70% of total irrigation	2.71	0	2.79	0
60% of total irrigation	2.62	3.32	2.70	3.23
50% of total irrigation	2.40	11.44	2.49	10.75

Table 4.23. Predicted cotton yield and its percent reduction under different deficit irrigation treatments using fresh and drainage water in the 1998 and 2002 cropping seasons at El-Serw site.

Growing season 1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	**Reduction (%)**	**Predicted yield (t/ha)**	**Reduction (%)**
Total irrigation	3.12	0	3.35	0
80% of total irrigation	2.91	6.73	3.19	4.78
70% of total irrigation	2.50	19.87	2.74	18.21
60% of total irrigation	1.88	39.74	2.11	37.01
50% of total irrigation	1.29	58.65	1.46	56.42

Growing season 2002

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	**Reduction (%)**	**Predicted yield (t/ha)**	**Reduction (%)**
Total irrigation	1.71	0	2.07	0
80% of total irrigation	1.71	0	2.07	0
70% of total irrigation	1.66	2.92	2.07	0
60% of total irrigation	1.43	16.37	1.85	10.63
50% of total irrigation	1.06	38.01	1.40	32.37

20% of the full irrigation requirement is not recommended for crop production in El-Serw site.

We can see from the data that the amount of irrigation water applied in El-Serw in 1999, correctly matches the water requirements for cotton.

A comparison of the data for the 1998 and 2002 growing seasons shows that 30% of the water applied could be saved without any significant reduction in yield. The recorded loss was around 3% compared to the yield obtained under full irrigation which suggests that ‘full irrigation’ was actually over irrigation.

A comparison of the data for the 1998 and 2002 growing seasons shows that 30% of the water applied could be saved without any significant reduction in yield. The recorded loss was around 3% compared to the yield obtained under full irrigation which suggests that ‘full irrigation’ was actually over irrigation.

Predicted CWU for cotton under deficit irrigation – Beni Sweif site

Table 4.24 shows the predicted CWU, and its changes under deficit irrigation treatments, during four successive experimental seasons (1997 to 2001) for a cotton crop at the Beni Sweif site.

The data indicate that the reduction in CWU of the cotton crop followed a trend similar to that for the predicted yield reductions. As the volume of irrigation water was decreased so there was an accompanying decrease in the yield. This held true for both the fresh and drainage water irrigation scenarios. However, the magnitudes of the changes in yield associated with the different treatments varied greatly from one cropping season to the other. In addition, the data show that under the different deficit irrigation treatments, the percent reductions in the volumes of irrigation water used were always greater than the

Table 4.24. Percent reduction in predicted yield and CWU for cotton grown under different deficit irrigation treatments at the Beni Sweif site in the 1997 to 2001 growing seasons.

Growing season 1997

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	**Predicted CWU reduction (%)**	**Predicted yield reduction (%)**	**Predicted CWU reduction (%)**
Total irrigation	0	0	0	0
80% of total irrigation	0	0	0	0
70% of total irrigation	0	0	0	0
60% of total irrigation	0.26	0.18	0.23	0.11
50% of total irrigation	1.84	8.86	0.92	5.27

Growing season 1998

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	**Predicted CWU reduction (%)**	**Predicted yield reduction (%)**	**Predicted CWU reduction (%)**
Total irrigation	0	0	0	0
80% of total irrigation	1.43	1.71	0.45	0.21
70% of total irrigation	1.90	5.58	1.36	4.94
60% of total irrigation	11.43	19.58	7.27	15.24
50% of total irrigation	26.19	38.86	20.45	34.12

Growing season 2000

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	**Predicted CWU reduction (%)**	**Predicted yield reduction (%)**	**Predicted CWU reduction (%)**
Total irrigation	0	0	0	0
80% of total irrigation	1.85	5.49	0.96	5.75
70% of total irrigation	7.38	13.73	6.11	12.86
60% of total irrigation	15.38	24.45	13.83	22.31
50% of total irrigation	25.85	39.04	24.67	35.55

Growing season 2001

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	**Predicted CWU reduction (%)**	**Predicted yield reduction (%)**	**Predicted CWU reduction (%)**
Total irrigation	0	0	0	0
80% of total irrigation	0	1.44	0	1.43
70% of total irrigation	0	5.58	0	4.38
60% of total irrigation	3.32	15.14	3.23	13.89
50% of total irrigation	11.44	28.97	10.75	26.40

accompanying reductions in the yield. Moreover, by comparing the reductions in yield and CWU under the different deficit irrigation treatments, it can be seen that the percent reductions in yield under the drainage water treatments were lower than those found under irrigation with freshwater.

These variations in the yield values obtained, which are larger under freshwater irrigation than drainage water irrigation, could be attributed to the effect of drainage water on the vegetative growth. The drainage water reduced vegetative growth and development and, hence, reduced the CWU. This is very apparent when irrigation was practiced with volumes corresponding to 50% of the total irrigation.

Predicted cotton yield under deficit irrigation – El-Serw site

For El-Serw site (see Table 4.25), it is quite clear that, during the 1999 and 2002 growing seasons, the CWU as well as the yields of cotton obtained under the different deficit irrigation treatments followed a trend similar to the one previously discussed for the Ben Sweif site.

However, comparing the CWU for cotton at the two sites under investigation, it is quite clear that this parameter varies greatly with the variations in growing season and site.

For the 2002 season for the Beni Sweif site, the amounts of water used were relatively higher than those at El-Serw site in the same season. For the predicted percent CWU reduction, we found the opposite to be true. This parameter at El-Serw site was nearly two or three times greater than that at the Beni Sweif site. This was particularly evident under severe deficit irrigation treatments where irrigation was practiced with volumes of water amounting to 60% and 50% of the total irrigation volume.

For El-Serw site, the data also show that the predicted reductions in CWU and the yields associated with these reductions in

Table 4.25. Percent reduction in predicted yield and CWU of cotton grown under different deficit irrigation treatments at El-Serw site in the 1999 and 2002 growing seasons.

Growing season 1999

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction (%)
Total irrigation	0	0	0	0
80% of total irrigation	6.73	8.17	4.78	6.90
70% of total irrigation	14.87	24.66	18.21	23.01
60% of total irrigation	39.74	48.05	37.01	45.08
50% of total irrigation	58.65	68.95	56.42	67.40

Growing season 2002

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction (%)
Total irrigation	0	0	0	0
80% of total irrigation	0	0.80	0	0.12
70% of total irrigation	2.92	8.30	0	3.11
60% of total irrigation	16.37	22.16	16.63	15.44
50% of total irrigation	38.01	47.22	32.37	40.04

the in the volume of water applied, are greater for the 1999 growing season than for the 2002 season. This holds true for the investigated deficit irrigation treatments under both fresh water and drainage water irrigation. The variation in these two parameters in El-Serw site could be attributed to the differences in the climatic parameters between the 1999 and 2002 growing seasons.

Clover

Predicted clover yield under deficit irrigation

The data shown in Table 4.26 indicates that the gradual decrease in the volumes of irrigation water applied gradually reduced the clover yield. This was the case for four successive growing seasons. In the 1997-1998 growing season the clover yield under the fresh water irrigation treatments was an average of 4.95 t/ha, which corresponded to about 64% of the yields obtained in the following three successive seasons. The yields in these successive seasons were more or less similar under the different deficit irrigation treatments investigated.

Changing the irrigation water from fresh to drainage water did not result in any notable variations in the yield. During the growing season 1997-1998, under drainage water irrigation, the clover yield was slightly lower than that from freshwater; whereas in the 1998-1999 season it was slightly higher. Taking into consideration the two successive growing seasons 1999-2000 and 2000-2001, the variations in yield, resulting from irrigation with water of different qualities, was not significant – it remained essentially the same. Such data provide evidence that clover can be successfully irrigated with low salinity water, such as drainage water, without any notable deterioration in its yield.

The data indicate that irrigation under 90% of the full irrigation amount did not result in any notable losses in yield. Those that did occur varied from between 1.14% and 5.37% with an average value of 3.3%. This is a very satisfactory result since it represents a 10% saving in the amount of water to be applied water, while at the same time maintaining, a yield very close to that obtained when full irrigation is practiced. The data also show that for clover there are further potential savings of water while keeping the yield at values very similar to that when full irrigation is practiced. This was verified for the case where irrigation was practiced with 80% of the full irrigation volume. Irrigation under such volumes of water during four successive growing seasons resulted in an average yield reduction not exceeding 7% of that achievable under full irrigation.

For arid and semi-arid regions, such data are technically and economically sound. Furthermore, for areas suffering freshwater shortages, it is possible to irrigate clover with waters having a salinity level which the crop can tolerate, such as the drainage water in this case.

The beneficial effect will be the saving of relatively large quantities of freshwater, which can be used to expand the irrigated areas, compensating for water shortages in other sectors. The water saved can also be used to leach accumulated salts from the soil and to keep those soils under irrigation with saline water at a high productivity level.

Predicted water consumption for clover

Data concerning the percent reductions in predicted clover yield and the percent reductions in CWU during the four successive growing seasons – from 1997-1998 until 2000-2001 – under different deficit irrigation treatments are given in Table 4.27. The reductions in CWU for clover planted under fresh and drainage water deficit irrigation are shown in Figures 4.1 and 4.2.

The data show that under the deficit irrigation treatments, the percent reductions in the water used followed a trend similar to that characterizing the percent reductions for the clover yield. This clearly indicates the relationship that exists between the two parameters studied. The less the volume of irrigation water applied, the greater the percent decrease in both the clover yield

Table 4.26. Predicted clover yield and its percent reduction under different deficit irrigation treatments with fresh and drainage water.

Growing season 1997-1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	5.21	0	4.83	0
95% of total irrigation	5.04	3.26	4.74	1.86
90% of total irrigation	4.93	5.37	4.62	4.35
85% of total irrigation	4.84	7.10	4.45	7.87
80% of total irrigation	4.75	8.83	4.25	12.01

Growing season 1998-1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	7.88	0	8.74	0
95% of total irrigation	7.88	0	8.74	0
90% of total irrigation	7.79	1.14	8.74	0
85% of total irrigation	7.59	3.68	8.64	1.14
80% of total irrigation	7.34	6.85	8.42	3.66

Growing season 1999-2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	7.59		7.48	
95% of total irrigation	7.55	0.53	7.48	0.40
90% of total irrigation	7.42	2.24	7.39	1.60
85% of total irrigation	7.18	5.40	7.17	4.53
80% of total irrigation	6.91	8.96	6.96	7.32

Growing season 2000-2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	7.43	0	7.75	0
95% of total irrigation	7.16	3.63	7.45	3.87
90% of total irrigation	7.10	4.44	7.44	4.00
85% of total irrigation	6.98	6.06	7.36	5.03
80% of total irrigation	6.72	9.56	7.12	8.13

and CWU against their predicted values under full irrigation treatment. This was also the case when using drainage water for irrigation. However, under the drainage water irrigation scenario, during the four successive growing seasons, the percent reductions in water used were not equal to those predicted under irrigation with freshwater.

Generally, under irrigation with water of EC values exceeding that of fresh water, it is expected that the predicted percent reductions in the CWU under the deficit irrigation treatments would be lower than those obtained when irrigating with freshwater. This was quite evident for cotton.

For clover irrigated with drainage water, the percent reductions in the water used under the deficit irrigation treatments were either very near to or slightly greater than those predicted when irrigation was practiced with freshwater. Such dissimilarities in this parameter could be attributed to variations in the yield produced and the predicted yield losses under both irrigation water treatments.

Soybean crop

Predicted soybean yield under deficit irrigation

Soybean is one of the oil crops which is receiving attention from many researchers in Egypt. The germination stage is the most critical one as it requires an accurate irrigation regime. Irrigation with either too much or not enough water than needed will result in reducing seed germination and, thereby, lowering the final yield produced.

The predicted yield and the percent reductions under different deficit irrigation treatments for four successive growing seasons between 1998 and 2001 are presented in Table 4.28 and Figures 4.3 and 4.4.

The data indicate that, generally, under deficit irrigation treatments, the soybean crop followed a trend similar to those previously discussed for both cotton and clover. Taking the total irrigation as the reference, it is apparent that there is a reduction in the yield associated with a decrease in the volumes of irrigation water applied. This is also true for the yield data obtained during four growing seasons. Under irrigation with freshwater, the data show that irrigation with a water volume corresponding to 95% of the full irrigation treatment, (a 5% saving in water) did not result in any significant difference in the soybean yield – the values are more or less the same as those obtained under the full irrigation treatment.

This was also the case when the water saving was doubled from 5% to 10%. Under the 10% water saving treatment, the yield reduction during the four growing seasons averaged 2.2%, just 1.2% more losses in yield than were obtained with the 5% water saving treatment. When water saving was increased from 10% to 20%, the losses in the yield remained relatively low and did not exceed, on average, 8% with respect to that obtained under full irrigation.

In arid regions where water is the limiting factor to achieving food security, such results are satisfactory for soybean as well as the other crops studied at the Beni Sweif site. Under deficit irrigation techniques, the reductions in the amount of water applied result, to a certain extent, in a win-win situation. Not only is there potential for a large saving in water, but also a satisfactory yield production is maintained without any harmful losses.

The deficit irrigation treatments investigated showed a trend similar to those discussed for the freshwater treatments. They show slightly lower yields with the successive decreases in the volumes of irrigation water. However, for the four growing seasons investigated, the soybean yield, with a few exceptions, showed values which were always slightly lower than those obtained under the freshwater treatments.

In 1998, the yield obtained under irrigation with drainage water was, on average, nearly 10% more than that obtained under

Table 4.27. Predicted percent reduction in clover yield and CWU under different deficit irrigation treatments using fresh and drainage water during successive growing seasons from 1997-1998 to 2000- 2001 at Beni Sweif site.

Growing season 1997-1998

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction (%)
Full irrigation	0	0	0	0
95% of total irrigation	3.20	0.44	1.86	0.18
90% of total irrigation	5.37	1.05	4.35	1.01
85% of total irrigation	7.10	2.10	7.87	2.82
80% of total irrigation	8.83	3.64	12.01	6.17

Growing season 1998-1999

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	0	0	0	0
90% of total irrigation	1.14	0.05	0	0.10
85% of total irrigation	3.68	0.54	1.14	0.10
80% of total irrigation	6.85	1.91	3.60	0.54

Growing season 1999-2000

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU Reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	0.53	0.27	0.40	0.73
90% of total irrigation	2.24	1.02	1.60	0.50
85% of total irrigation	5.40	2.85	4.53	0.53
80% of total irrigation	8.96	6.30	7.32	2.94

Growing season 2000-2001

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted CWU reduction (%)	Predicted yield reduction (%)	Predicted CWU reduction %()
Total irrigation	0	0	0	0
95% of total irrigation	3.63	1.17	3.87	2.60
90% of total irrigation	4.44	1.87	4.00	2.92
85% of total irrigation	6.06	3.81	5.03	4.29
80% of total irrigation	9.50	7.29	8.13	7.11

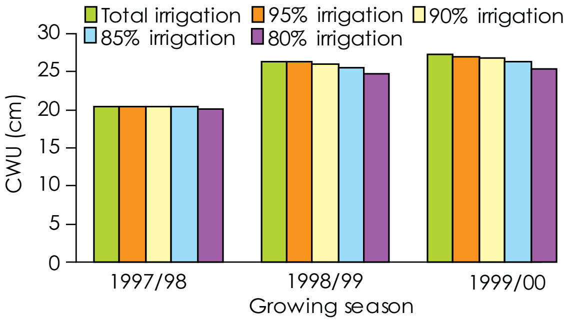

Figure 4.1. The CWU for clover planted at Beni Sweif under different fresh water deficit irrigation treatments for three growing seasons.

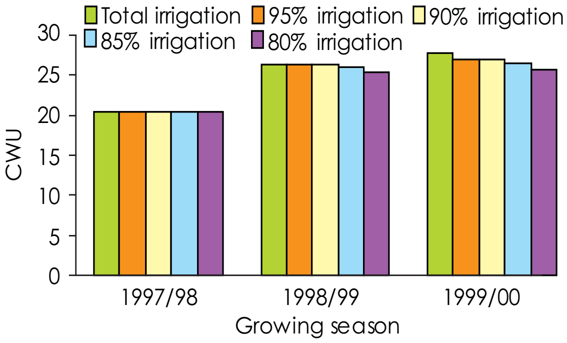

Figure 4.2. The CWU for clover planted at Beni Sweif under different drainage water deficit irrigation treatments for three growing seasons.

freshwater irrigation, whereas it amounted to just 85% of the freshwater yield in the next two successive growing seasons, 1999 and 2000. In 2001 it drastically dropped to an average value nearly 50% lower than that obtained with freshwater. This could be attributed to changes in the EC values of the drainage water from one crop season to the next

Predicted water use of soybean under deficit irrigation

The predicted reductions in soybean yields and water used under different deficit irrigation treatments as compared to the full irrigation treatments are presented in Figures 4.5 and 4.6 and Table 4.29. They show the reductions in CWU for soybean planted under fresh and drainage water deficit irrigation.

The data show that under deficit irrigation, gradually decreasing the volume of water applied affected the CWU of soybean, gradually decreasing its value with respect to that when full irrigation was practiced. This holds true under irrigation with freshwater as well as with drainage water. However, under drainage water practices and for the four cropping seasons considered, the reductions in CWU as percentages of the full irrigation treatment had values that, in general, were lower than the ones predicted for irrigation under fresh water. This could be explained by the fact that under irrigation with drainage water, the percent reductions in yield were relatively lower than the ones obtained when irrigating with freshwater, and this was the opposite of that concerning water use.

Wheat

Predicted wheat yield under deficit irrigation

The predicted wheat yield for four successive growing seasons (between 1998-1999 and 2000-2001) under different fresh and drainage water irrigation treatments, and its reduction, expressed as a percentage of the yield produced under a total irrigation treatment, are presented in Table 4.30.

The data presented in Table 4.30 clearly show that wheat is one of the crops among those studied that can be grown successfully with smaller volumes of water applied without it having a significant effect on the yield. The data obtained under the different deficit irrigation treatments investigated for the successive growing seasons show that irrigation with volumes of water 30% less than that used for full irrigation gave an average yield of 5.52 t/ha. This compares favorably to the average yield of 5.88 t/ha for the full

Table 4.28. Predicted yield and percent reduction for soybean grown under different deficit irrigation treatments for four successive growing seasons, 1998-2001.

Growing season 1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	1.20	0	1.33	0
95% of total irrigation	1.19	0.83	1.32	0.75
90% of total irrigation	1.17	2.50	1.29	3.01
85% of total irrigation	1.15	4.17	1.26	5.26
80% of total irrigation	1.12	6.67	1.21	9.02

Growing season 1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	2.24	0	1.77	0
95% of total irrigation	2.22	0.89	1.75	1.13
90% of total irrigation	2.16	3.57	1.72	2.82
85% of total irrigation	2.07	7.59	1.68	5.08
80% of total irrigation	2.04	8.93	1.62	8.47

Growing season 2000

Irrigation	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	1.70	0	1.54	0
95% of total irrigation	1.69	0.59	1.53	0.65
90% of total irrigation	1.67	1.76	1.50	2.60
85% of total irrigation	1.63	4.12	1.47	4.55
80% of total irrigation	1.58	7.06	1.43	7.14

Growing season 2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	1.67	0	0.86	0
95% of total irrigation	1.65	1.20	0.85	1.16
90% of total irrigation	1.61	3.59	0.83	3.49
85% of total irrigation	1.58	5.39	0.82	4.65
80% of total irrigation	1.53	8.38	0.80	6.98

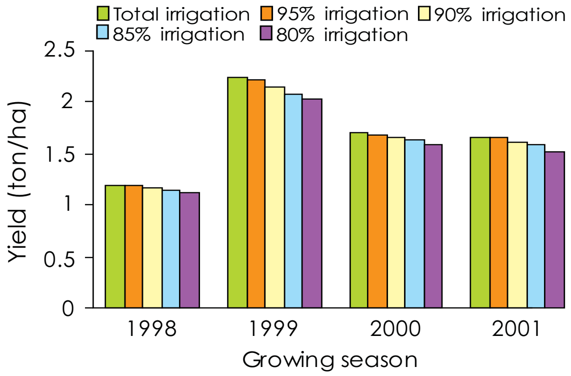

Figure 4.3. Soybean yields under different fresh water deficit irrigation for four growing seasons at Beni Sweif.

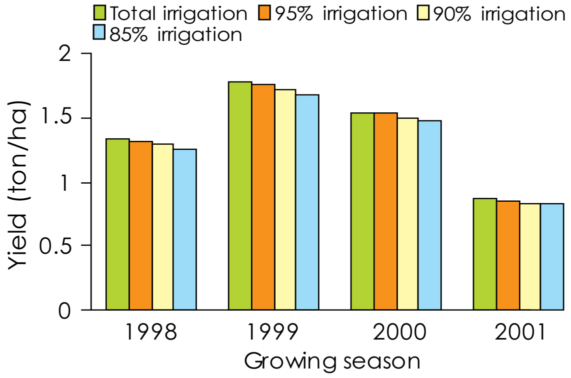

Figure 4.4. Soybean yields under different drainage water deficit irrigation for four growing seasons at Beni Sweif.

irrigation treatment. and represents a 6% reduction on average. Furthermore, the yield data, when irrigation was practiced with 80% of the full irrigation volumes, show no significant reduction in yield – the values were nearly equal to those obtained under full irrigation and represent an average yield loss of around 2.3%.

Such data should be translated into actions to be implemented on the ground. Egypt, at the national level, produces only 50% of the wheat required to satisfy its needs, while the other 50% is imported from abroad. The annually increasing demands for wheat throw increasing demands on the foreign currency resources of the country to pay for this imported supply. Such a situation creates serious problems, notably and negatively affecting not only the national income, but, equally, the economic and social development programs.

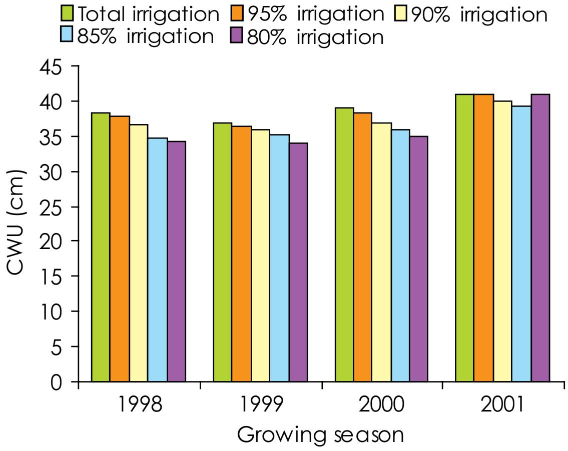

Figure 4.5. The CWU for soybean planted at Beni Sweif under different fresh water deficit irrigation treatments for four growing seasons.

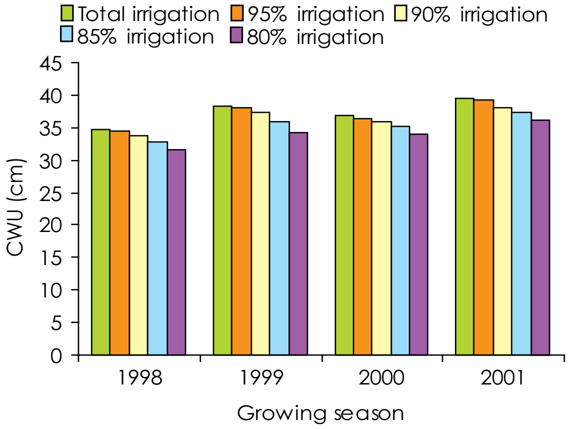

Figure 4.6. The CWU for soybean planted at Beni Sweif under different drainage water deficit irrigation treatments for four growing seasons.

A sustainable solution to the problem lies in increasing national wheat production to reduce the relatively high import costs

Table 4.29. Percent reduction in predicted yield and CWU for soybean grown under different deficit irrigation treatments in four growing seasons between 1998 and 2001, at Beni Sweif site.

Growing season 1998

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted WU reduction (%)	Predicted yield reduction (%)	Predicted WU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	0.83	1.02	0.75	1.01
90% of total irrigation	2.50	2.46	3.01	2.94
85% of total irrigation	4.17	4.52	5.26	5.70
80% of total irrigation	6.67	7.66	9.02	9.01

Growing season 1999

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted WU reduction (%)	Predicted yield reduction %	Predicted WU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	0.89	1.10	1.13	0.73
90% of total irrigation	3.57	4.08	2.82	2.32
85% of total irrigation	7.59	9.24	5.08	6.24
80% of total irrigation	8.93	10.40	8.47	10.86

Growing season 2000

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted WU reduction (%)	Predicted yield reduction (%)	Predicted WU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	0.59	1.17	0.65	1.17
90% of total irrigation	1.76	2.56	2.60	2.77
85% of total irrigation	4.12	4.44	4.55	4.70
80% of total irrigation	7.06	7.40	7.14	7.52

Growing season 2001

Irrigation treatment	Fresh water		Drainage water	
	Predicted yield reduction (%)	Predicted WU reduction (%)	Predicted yield reduction (%)	Predicted WU reduction (%)
Total irrigation	0	0	0	0
95% of total irrigation	1.20	1.94	1.16	0.94
90% of total irrigation	3.56	5.50	3.49	3.84
85% of total irrigation	5.39	8.00	4.65	5.71
80% of total irrigation	8.38	10.53	6.98	8.42

Table 4.30. Wheat yield under different deficit irrigation treatments in the growing seasons 1998-2001 at Beni Sweif site.

Growing season 1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	5.28	0	5.23	0
90% of total irrigation	5.27	0.19	5.22	0.19
85% of total irrigation	5.26	0.38	5.19	0.76
80% of total irrigation	5.16	2.27	5.16	1.34
70% of total irrigation	5.07	3.98	5.07	3.06

Growing season 1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	5.73	0	4.73	0
90% of total irrigation	5.72	0.17	4.73	0
85% of total irrigation	5.68	0.87	4.72	0.21
80% of total irrigation	5.68	0.87	4.71	0.42
70% of total irrigation	5.52	3.66	4.61	2.54

Growing season 2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	5.73	0	6.31	0
90% of total irrigation	5.71	0.35	6.30	0.16
85% of total irrigation	5.69	0.70	6.26	0.79
80% of total irrigation	5.59	2.44	6.19	1.90
70% of total irrigation	5.31	7.33	5.89	6.66

Growing season 2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	6.79	0	6.52	0
90% of total irrigation	6.70	1.33	6.45	1.07
85% of total irrigation	6.65	2.06	6.36	2.45
80% of total irrigation	6.53	3.83	6.27	3.83
70% of total irrigation	6.18	8.98	5.97	8.44

which the country is incurring to meet the shortage in local wheat production.

For Egypt, wheat is a strategic crop, which provides bread – the essential food to feed the increasing population. In this regard, the questions which are now under continuous debate are, "At the national level, can Egypt satisfy its needs for wheat? And if so, what tools and means need to be implemented to achieve such a goal?" The answer to these questions is not easy. Theoretically, the possibility exists, but technically it is not an easy process. However, through effective work, appropriate planning, the introduction of new technologies, improvement of the capacities of national and local institutions, and by developing and updating people's skills, what is now a questionable objective, will be, in the long-term, a realistic one.

The data obtained in this long-term program favors the idea that, in the long run, a good opportunity to increase wheat production does exist. Implementing this opportunity will gradually reduce the gap between the amounts of wheat produced and consumed locally.

It is well recognized that for most arid regions, water is the main limiting factor to increasing production of most crops, including wheat. However, wheat, as compared with the previously studied crops, seems to be more tolerant to water-stress conditions. This is quite evident from the data. Hence, irrigating wheat with volumes of water corresponding to about two-thirds of that representing its actual water requirement will result in a yield nearly similar to that obtained under full irrigation. On average the yield loss would be around 5%. This means that with less water, we can have virtually the same production. Such data have been obtained under a 30% water saving on the volume traditionally applied. This again indicates that by increasing the water saving from 30% to 40%, and even up to 50%, it is possible to achieve a satisfactory wheat production without any notable losses in yield.

As can be seen, we can have more or less the same wheat yield with water savings ranging from 30% up to 50% of the total water requirement of the crop. Combine this with the new wheat varieties, identify the correct irrigation scheduling to be implemented at the different growth stages – enabling tools and means that should be effectively and properly used – and support these efforts with the needed research, and we should be able to bridge the seriously increasing gap between wheat supply and demand.

Predicted water use by wheat under deficit irrigation

In comparison with the other crops studied, wheat showed more tolerance to water stress conditions under deficit irrigation technique, even when the amount of water applied was reduced up to 30%. The reductions in predicted yields as well as those in CWU under the investigated deficit irrigation treatments are shown in Table 4.31. The CWU for wheat planted under different fresh and drainage water deficit irrigation treatments are shown in Figures 4.7 and 4.8.

As shown in Table 4.30 and Figures 4.7 and 4.8, it is quite apparent that under the different deficit irrigation treatments investigated, the reduction in the CWU with respect to the full irrigation treatment followed a trend similar to that characterizing the losses in wheat production. The lower the volume of applied water; the higher is the reduction in both the CWU of wheat and its yield.

This holds true for irrigation with both fresh and drainage water. However, for the deficit drainage water irrigation treatments, the percent reductions in the CWU were slightly smaller than those predicted under the freshwater irrigation treatments. This is clearly seen when comparing the percent reductions in CWU in the 1998 and 1999 growing seasons with those of the 2000 and 2001 seasons and, particularly, those achieved under the relatively high 30% water saving treatments. Under the deficit irrigation

Table 4.31. Percent reductions in wheat production and CWU under different deficit irrigation treatments during successive growing seasons (1998-2001) at Beni Sweif site.

Growing season 1998

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield reduction (%)	Reduction in CWU (%)	Predicted yield reduction (%)	Reduction in CWU (%)
Total irrigation	0	0.29	0	0
90% of total irrigation	0.19	0.44	0.19	0.32
85% of total irrigation	0.38	2.36	0.76	0.95
80% of total irrigation	2.27	4.14	1.34	1.54
70% of total irrigation	3.98	0	3.06	3.90

Growing season 1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield reduction (%)	Reduction in CWU (%)	Predicted yield reduction (%)	Reduction in CWU (%)
Total irrigation	0	0	0	0
90% of total irrigation	0.17	0.26	0.00	0.02
85% of total irrigation	0.87	0.81	0.21	0.14
80% of total irrigation	0.87	0.96	0.42	0.38
70% of total irrigation	3.66	3.72	2.54	2.63

Growing season 2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield reduction (%)	Reduction in CWU (%)	Predicted yield reduction (%)	Reduction in CWU (%)
Total irrigation	0	0	0	0
90% of total irrigation	0.35	0.56	0.10	0.25
85% of total irrigation	0.70	1.13	0.70	1.08
80% of total irrigation	2.44	3.25	1.90	2.53
70% of total irrigation	7.33	9.54	6.66	8.82

Growing season 2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield reduction (%)	Reduction in CWU (%)	Predicted yield reduction (%)	Reduction in CWU (%)
Total irrigation	0	0	0	0
90% of total irrigation	1.33	1.55	1.07	1.55
85% of total irrigation	2.06	2.95	2.45	3.53
80% of total irrigation	3.83	5.45	3.83	5.45
70% of total irrigation	8.98	12.24	8.44	11.52

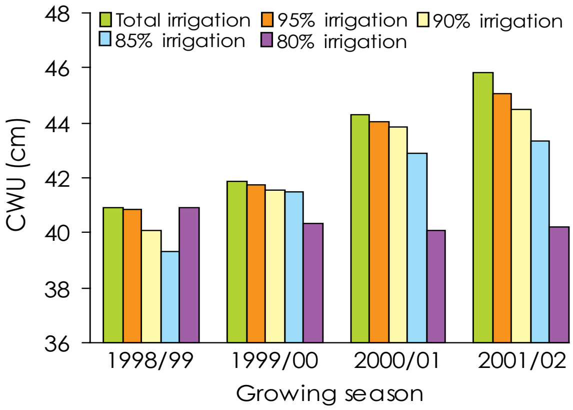

Figure 4.7. The CWU for wheat under different fresh water deficit irrigation treatments during four growing seasons at Beni Sweif.

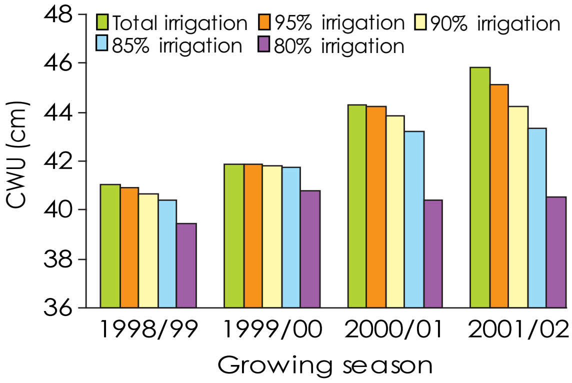

Figure 4.8. The CWU for wheat under different drainage water deficit irrigation treatments during four growing seasons at Beni Sweif.

treatments corresponding to 70% of full irrigation, the reductions in CWU for the 2000 and 2001 cropping seasons was between three and four times greater than those predicted in the previous growing seasons of 1998 and 1999. This holds true for irrigation with fresh as well as drainage water. Such reductions in CWU values with the change from one cropping season to another could be attributed to the changes in the wheat yield from one season to the next. However, a difference in consumptive water use arising from variations in the irrigation water quality could be due to the influence exerted by the drainage water on yield production, with these values being slightly lower than those obtained when irrigating with freshwater. This again confirms the existence of a strong relationship between yield and the CWU under irrigation with different volumes of water and waters of different qualities.

Faba bean

Faba bean is one of the essential food legumes of Egypt. It is a popular food for Egyptians and the amounts consumed are increasing from year to year – a result of the high rate of increase in population. From the 1980s to the 1990s, Egypt achieved self sufficiency in this crop. However, Egypt has for some years been, and is now, experiencing a big gap between demand for and production of faba bean. This shortage in production has to be addressed by imports, which adds a heavy burden to the country's national budget. Government policy is to increase the production of several essential crops, particularly wheat and faba bean, where consumption is notably exceeding production.

An appropriate way to overcome such a gap is to increase crop production to meet the increasing demand. This is not an easy task. We have only few approaches to follow. An increase in crop production could be realized by augmenting the irrigated area. However, in the dry region, the shortage of available water and productive lands are major limiting factors impeding such a strategy.

An approach to be followed, without the need for additional water supplies, is by increasing the crop water productivity. That can be achieved by increasing the 'crop per drop' – increasing the yield with the same amount of water. Improving crop water productivity could also be achieved by implementing deficit irrigation techniques through which we can have more or less the same yield using less water for irrigation. Water allocated to agriculture amounts to nearly 80% or more of the total available freshwater. Using deficit irrigation, there is the high potential to save ample amounts of irrigation water.. However, implementing deficit irrigation successfully on a large scale requires adequate, up-to-date knowledge based on experimental results and research findings in order to find an appropriate irrigation regime to be followed which provides, on the one hand, a satisfactory yield and, on the other, a significant saving of water.

Predicted yield of faba bean under deficit irrigation

The predicted yields (t/ha) under the different fresh and drainage water deficit irrigation treatments investigated, and their percent reductions in the three successive cropping seasons (from 1998-1999 to 2001-2002) at the Beni Sweif site, are given in Figures 4.9 and 4.10 and Table 4.32.

The data show that the gradual decrease in the volume of water applied resulted in a gradual reduction in the faba bean yield. However, under each deficit irrigation treatment, even that where irrigation was undertaken with a water volume 20% lower than that for full irrigation, the faba bean crops showed yields very similar to that obtained under full irrigation – the average yield reduction did not exceed 5% over all cropping seasons. This statement also holds true under irrigation with drainage water. However, the faba bean yields under the drainage water irrigation treatments showed values slightly lower than those when freshwater was used. Such not significant differences between faba bean yields under drainage water irrigation and freshwater irrigation, is evidence that faba bean can be successfully grown without any drastic drop in its yield, using drainage water of a salinity level that the crop can tolerate. In this case, using deficit irrigation techniques and irrigating with drainage water is a win-win game providing, on the one hand, a saving of freshwater and, on the other, a reduction in the degree of salt accumulation within the active root zone.

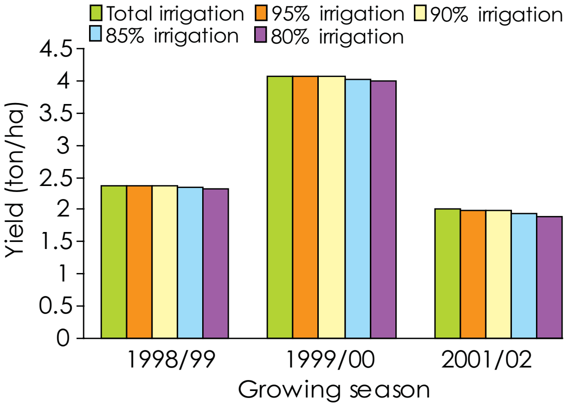

Figure 4.9. Faba bean yields under different fresh water deficit irrigation treatments for three growing seasons at Beni Sweif.

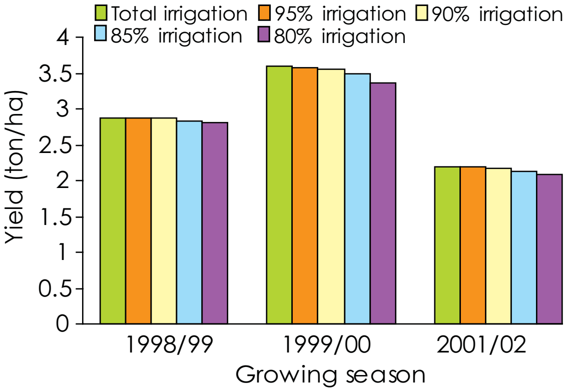

Figure 4.10. Faba bean yields under different drainage water deficit irrigation treatments for three growing seasons at Beni Sweif.

It is of special interest here that irrigation with a freshwater volume corresponding to 80% of the full irrigation requirement does not result in any drastic drop in yield. This suggests that it might be possible to grow a faba bean crop with a satisfactory yield with greater savings in the amount of water used – from 20% to 30% less, perhaps up to 40% less or much more. However, this has to be studied experimentally.

This was the main objective of the experimental work carried out during the course of the Project.

Table 4.32. Predicted faba bean yield under different irrigation treatments at the Beni Sweif site.

Growing season 1998-1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	2.88	0	2.37	0
95% of total irrigation	2.88	0	2.37	0
90% of total irrigation	2.87	0.35	2.37	0
85% of total irrigation	2.84	1.39	2.35	0.84
80% of total irrigation	2.81	2.43	2.33	1.69

Growing season 1999-2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	3.60	0	4.08	0
95% of total irrigation	3.58	0.56	4.07	0.25
90% of total irrigation	3.56	1.11	4.06	0.49
85% of total irrigation	3.49	3.06	4.03	1.23
80% of total irrigation	3.36	6.67	3.99	2.21

Growing season 2001-2002

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	2.20	0	2.00	0
95% of total irrigation	2.19	0.45	1.99	0.50
90% of total irrigation	2.17	1.36	1.98	1.00
85% of total irrigation	2.13	3.18	1.95	2.50
80% of total irrigation	2.08	5.45	1.90	5.00

Onions

Predicted onion yield under deficit irrigation

The predicted onion yield and its percent reductions under different deficit irrigation treatments are presented in Table 4.33 and Figures 4.11 and 4.12.

The data in Table 4.33 indicate that onion could be grown successfully under deficit irrigation practices. For all growing seasons, irrigation with 80% of the full irrigation requirement (a 20% saving in water) did not result in any significant differences in the onion yields, they were more or less the same as those achieved under full irrigation.

The differences in onion production between a full irrigation treatment and the highest deficit irrigation one did not exceed, on average, 2% for all the growing seasons. This also holds true for irrigation

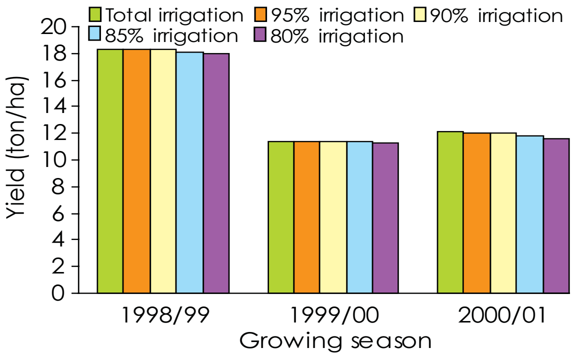

Figure 4.11 Onion yields under different fresh water deficit irrigation treatments for three growing seasons at Beni Sweif.

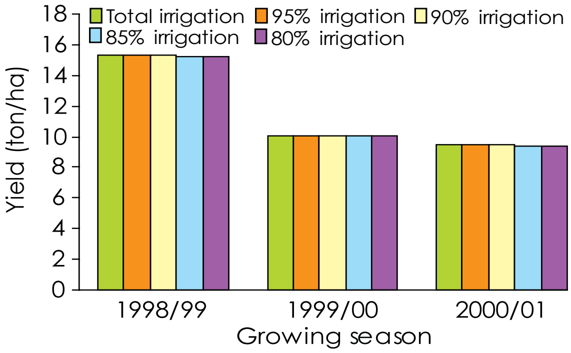

Figure 4.12. Onion yields under different drainage water deficit irrigation treatments for three growing seasons at Beni Sweif.

under fresh and drainage water treatments. However, in comparison with the crops discussed previously, it is quite clear that onion are more affected. Looking at the yield under full irrigation, it can be seen that for the freshwater treatment, the yield was, on average, nearly 17% higher than the yield where drainage water irrigation was used. This was also the case under the different deficit irrigation treatments investigated. The yield under the drainage water irrigation treatments was always lower than that obtained under the similar fresh water one. Such findings could be attributed to the high sensitivity of onion to the salinity level of the irrigation water.

The data for the predicted yields under the different deficit irrigation treatments (Table 4.33), show that under the drainage water irrigation treatments the reductions in the onion yield, compared that achieved when providing the full water requirement, were relatively small, amounting to just one-half, or in some cases, one-third or even less. Such data indicate that the onion crop is more resistant to water stress rather than to salt stress.

As previously mentioned, the minimum reduction in the onion yield due to deficit irrigation with fresh water, amounted to just 2% of that achieved under full irrigation. This was accompanied by a 20% saving in water, which, again, confirms that onion can tolerate water stress conditions. Thus onion can be grown successfully without any drastic drop in yield using volumes of water below that currently used, which will lead to further water savings.

4.3.3 Model validation using current experimental field data

Yield-Stress model validation under the application of there was a notable total irrigation amounts

The data below show no or very little stress, because the CWU is essentially not affected. This would not be considered as a deficit unless reduction in CWU (i.e., evapotranspiration).

For El-Monofia site, the percent difference between the measured and predicted yields was less than 0.5 (Table 4.34). The highest difference in water use was obtained for the first farm.

For El-Serw site, there was no difference between the measured and predicted yields (Table 4.35). This is an indication that the amount of irrigation water applied was enough to meet the evapotranspiration demand. Furthermore, the difference between measured and predicted water use was less than 0.5%, except for Farm 4, where it was 1.63% (Table 2.35).

Table 4.33: Predicted onion yield and its percent reduction under different deficit irrigation treatments during the successive cropping seasons 1998-2002 at Ben Sweif site.

Growing season 1998-1999

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	18.33	0	15.30	0
95% of total irrigation	18.33	0	15.29	0.07
90% of total irrigation	18.29	0.22	15.28	0.13
85% of total irrigation	18.12	1.15	15.26	0.26
80% of total irrigation	18.02	1.69	15.24	0.39

Growing season 1999-2000

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	11.42	0	10.06	0
95% of total irrigation	11.42	0	10.06	0
90% of total irrigation	11.41	0.09	10.05	0.10
85% of total irrigation	11.39	0.26	10.04	0.20
80% of total irrigation	11.31	0.96	10.01	0.50

Growing season 2000-2001

Irrigation treatment	Fresh water irrigation		Drainage water irrigation	
	Predicted yield (t/ha)	Reduction (%)	Predicted yield (t/ha)	Reduction (%)
Total irrigation	12.09	0	9.48	0
95% of total irrigation	12.07	0.17	9.47	0.11
90% of total irrigation	12.00	0.74	9.45	0.32
85% of total irrigation	11.86	1.90	9.39	0.95
80% of total irrigation	11.60	4.05	9.35	1.37

Yield-Stress model validation under deficit irrigation

The model was used to predict wheat yields following deduction of about 20% of the total irrigation water at El-Monofia site (Table 4.36). The predicted wheat yield was close to the measured one for two of the three farms. The root mean square error (RMSE) was 0.048 and Willmott index of agreement was 0.977. Predicted water use was also close to the measured water use, except for the third farm. The RMSE was 0.040 and Willmott index of agreement was 0.999. Regression analysis between measured and predicted wheat yields at El-Monofia site had a significant linear relationship ($P < 0.05$), with equation

$$y = -2.278 + 1.278x \ (R^2 = 0.991).$$

For El-Serw site, there was good agreement between the measured and predicted wheat yields and the water use at three of the four farms. The percent difference between the measured and predicted yields and the water use was high for the fourth farm. The RMSE for the yield was 0.039 and that for water use was 0.040. The Willmott index of agreement was 0.999 for both yield and water use (Table 4.37). A statistically significant linear relationship ($P < 0.01$) between the measured and predicted wheat yields at El-Serw site was found with a linear regression equation

$$y = 0.129 + 0.978x (R^2 = 0.999).$$

Tested scenario of deficit irrigation

It was of special interest to use the Yield-Stress model to predict wheat yield under a deficit irrigation treatment using 30% less

Table 4.34. Measured versus predicted wheat yield and CWU at El-Monofia site.

Farm	Yield (t/ha)		Difference (%)	CWU (m^3)		Difference (%)
	Measured	Predicted		Measured	Predicted	
Farm 1	9.43	9.41	0.21	32.15	31.58	1.77
Farm 2	7.61	7.61	0	31.22	31.15	0.22
Farm 3	7.75	7.74	0.13	32.15	31.90	0.78

Note: CWU – consumptive water use.

Table 4-35. Measured versus predicted wheat yield and CWU at El-Serw site.

Farm	Yield (t/ha)		Difference (%)	CWU (m^3)		Difference (%)
	Measured	Predicted		Measured	Predicted	
Farm 1	5.60	5.60	0	31.86	31.99	0.41
Farm 2	5.25	5.25	0	31.28	31.42	0.45
Farm 3	4.55	4.55	0	33.74	33.62	0.36
Farm 4	6.20	6.20	0	34.38	34.94	1.63

Note: CWU – consumptive water use.

Table 4.36. Measured versus predicted wheat yield and CWU at El-Monofia site after deducting 20% of the total irrigation water.

Farm	Yield (t/ha)		Difference (%)	CWU (m^3)		Difference (%)
	Measured	Predicted		Measured	Predicted	
Farm 1	9.43	9.18	2.65	30.54	30.68	0.45
Farm 2	7.39	7.45	0.81	30.60	30.99	1.29
Farm 3	6.64	7.07	6.48	30.54	28.86	5.51
RMSE	0.048			0.040		
Willmott index	0.977			0.999		

Note: CWU – consumptive water use.

Table 4.37. Measured versus predicted wheat yield and CWU at El-Serw site after deducting 25% of the total irrigation water.

Farm	Yield (t/ha)		Difference (%)	CWU (m^3)		Difference (%)
	Measured	Predicted		Measured	Predicted	
Farm 1	5.50	5.50	0	30.27	31.22	3.15
Farm 2	5.15	5.11	0.78	29.72	30.26	1.83
Farm 3	4.40	4.37	0.68	32.05	31.98	0.23
Farm 4	5.70	6.05	6.14	32.14	33.94	5.58
RMSE	0.039			0.040		
Willmott index	0.999			0.999		

Note: CWU – consumptive water use.

water than that used for full irrigation. The model was used at El-Monofia site (Table 4.38-A). The value of the yield of the third farm was excluded from the prediction because the percent difference between the measured and predicted wheat yields under deficit irrigation was high. Therefore, only the first two farms were included in Table 4.38-A. The results in that table indicate that the wheat yield at that site might be reduced by 5.40% if the amount of irrigation water applied was reduced by 30%. At El-Serw site, the yield of the fourth farm was excluded from the analysis. The results in Table 4.38-B show that by saving 30% of the total applied irrigation water, the wheat yield would be reduced by 5.94%.

The data indicate that the measured wheat production varied greatly from one site to another. At El-Monofia site, the measured yield had an average value nearly 40% higher than that obtained at the Damietta site. For both sites, the experiments were carried out during the same growing season using the same irrigation regime and, therefore, such notable variation from on site to another could be attributed to variation in soil productivity as well as to differences in climatic factors.

In addition, the data showed the similarity between the measured and the predicted wheat yield at both sites, indicating the validity of the model.

Table 4.38-A. Measured and predicted wheat yield at Monofia site, 2005-2006 growing season.

Farm	Yield (t/ha)		Reduction (%)
	Measured	Predicted	
Farm 1	9.43	8.92	5.41
Farm 2	7.61	7.20	5.39
Average	8.52	8.06	5.40

Table 4-38-B. Measured and predicted wheat yield at Damietta site, 2005-2006 growing season.

Farm	Yield (t/ha)		Reduction (%)
	Measured	Predicted	
Farm 1	5.60	5.14	8.20
Farm 2	5.25	5.00	4.76
Farm 3	4.55	4.33	4.84
Average	5.13	4.82	5.94

It can be seen that saving 30% of the water applied resulted in yield losses not exceeding 6%. This is a very promising result, and draws attention to the high potential for water savings, amounting to 40% or 50%

of the full irrigation volume, when cropping wheat. However, care must be taken to avoid water stress of the crop during the sensitive growth stages. In this regard, much research work and many studies have been carried out by several workers and they generally came to the conclusion that for wheat, the germination and seedling stages are very sensitive to water shortage and that seed germination failure will be reflected in the final yield produced. Their data, also, indicated that both flowering and seed filling are crucial stages where any shortage of water will result in a drastic drop in wheat production. Accordingly, increasing the amount of water saved under wheat cropping and obtaining a satisfactory production is not difficult. What is needed is to set up an appropriate irrigation schedule that will fulfill the water requirement of the wheat growth stages according to their sensitivity and/or their resistance to water stress conditions.

4.3.4. Using the Yield-Stress model as an irrigation management tool

El-Monofia site

At El-Monofia site, the second farm was chosen because there was plenty of readily available water at the root zone after the fifth and sixth irrigations (Figure 4.13).

Therefore, the amounts of these two irrigations were reduced (Figure 4.14) and this saved around 22% of the water applied and the resulting yield loss was 0.13% (Table 4.39).

El-Serw site

Similar results were obtained for the third farm at El-Serw site. This farm was selected because there was also plenty of readily available water at the root zone after the fourth, fifth, and sixth irrigations (Figure 4.15). For that reason, the amounts of these three irrigations was reduced (Figure 4.16) leading to an approximate 24% saving in the amount of water applied with no yield loss (Table 4.39).

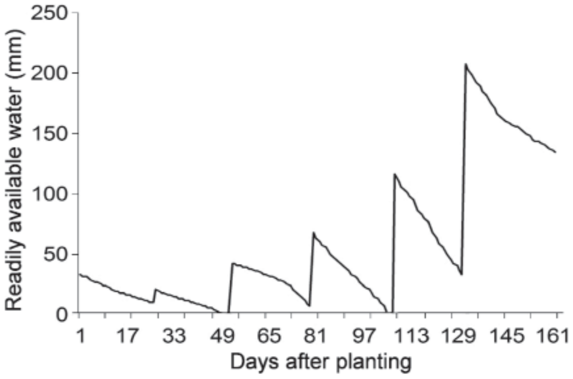

Figure 4.13. Depletion of the readily available water at the root zone after the application of each individual irrigation for wheat under the total irrigation amount (El-Monofia, Farm 2).

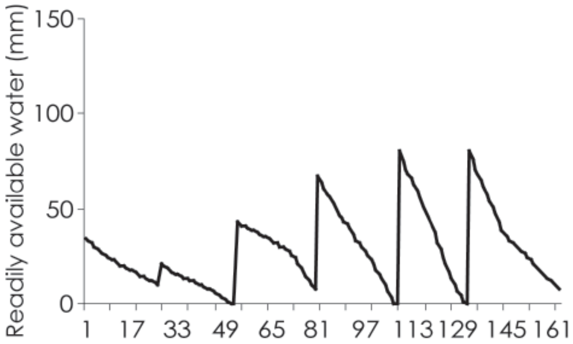

Figure 4.14. Depletion of the readily available water at the root zone after the application of each individual irrigation for wheat at 78% of the total irrigation amount (El-Monofia, Farm 2).

Table 4.39. Amount of irrigation water saved and corresponding reduction in yield at the three sites

Site	Amount of irrigation water saved (%)	Yield reduction (%)
Beni Sweif: 1999-2000	21	0
El-Monofia: farm 2	22	0.13
El-Serw: Farm 3	24	0

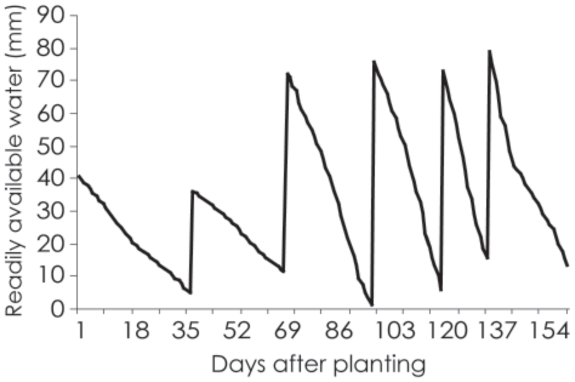

Figure 4.15. Depletion of the readily available water at the root zone after the application of each individual irrigation for wheat grown under the total irrigation amount (El-Serw, Farm 3).

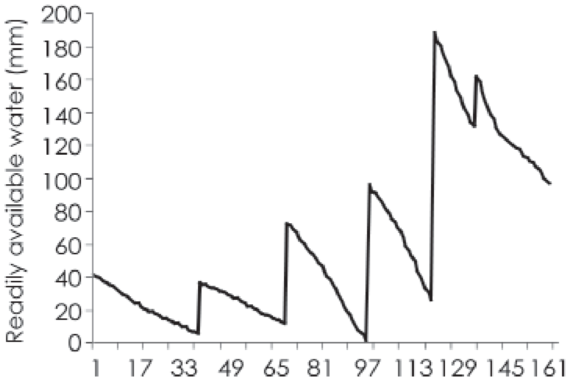

Figure 4.16. Depletion of the readily available water at the root zone after the application of each individual irrigation for wheat grown under the total irrigation amount (El-Serw, farm 3).

The above results suggest that using the model when studying the depletion of readily available water could be very helpful in saving irrigation water and in reducing unnecessary water losses, while maintaining a minimal yield reduction. At El-Monofia and El-Serw sites, around 22% and 24% of the total amount of irrigation water applied was saved with very low or no yield losses.

4.3.5 Yield-Stress model validation under salinity stress

Under salinity stress and applying the total irrigation amounts, the model overestimated wheat yield by 1.11% for Farm 1 and 0.60% for Farm 2. Under deficit irrigation, the model over predicted wheat yield for Farm 1 by 0.96%, while it under predicted the yield of Farm 2 by 1.52%. This result implied that the model can predict wheat yield under salinity stress and under salinity and water stresses (Table 4.40).

4.3.6 Tested deficit irrigation scenario

The measured and predicted wheat yields at the Damietta site using drainage water with a high level of salinity at volumes 30% lower than that for full irrigation are given in (Table 4.41).

The data presented indicate that deficit irrigation with drainage water in an amount equal to that of the fresh water does not notably affect the yield; the average yield losses were around 23% when compared with the yield obtained using the same amount of freshwater. The percent

Table 4.40. Measured versus predicted wheat yield under full and deficit irrigation.

Farm	Yield under full irrigation (t/ha)		Difference (%)	Yield under deficit irrigation (t/ha)		Difference (%)
	Measured	Predicted		Measured	Predicted	
Farm 1	4.52	4.57	1.11	4.15	4.19	0.96
Farm 2	3.35	3.37	0.60	3.30	3.25	1.52

Table 4.41. Measured and predicted wheat yield at Damietta, 2005-2006 growing season.

Farm	Yield (t/ha)		Reduction (%)
	Measured	Predicted	
Farm 1	4.52	3.77	16.59
Farm 2	3.35	2.91	13.13
Average	3.94	3.34	14.86

reductions in wheat yield under drainage irrigation was nearly 3 times greater than those when freshwater was used.

Such notable reductions in yield under drainage irrigation could be explained by the fact that irrigation was practiced with 70% of the total required volume of water. Therefore, the subsequent successive irrigations resulted in a rapid accumulation of salts in the active root zone to a level that the wheat could not tolerate. Hence, during the experiment, leaching was completely absent and this could be the reason behind such an excessive reduction in wheat yield.

4.4 Summary and conclusions

Over the last two decades, models have become a major research tool for resource management. In arid regions, water scarcity on the one hand, and the important role of water conservation in the agricultural sector on the other, are driving drastic changes in the ways we use and manage water resources. Saving water in the irrigation sector through improvement of on-farm water use efficiency is now a must, and it requires the exploration of different water management practices. However, this could be an expensive and a long drawn out process. By using simulation models it could be easy to predict the effect on the yield of the primary crops cultivated under irrigation with less volumes of water than the full irrigation requirement.

In the different regions of Egypt, irrigation management can be done by modeling water depletion in the root zone under the application of different amounts of irrigation water. Models that simulate crop growth and water flow in the root zone can be powerful tools for extrapolating findings and conclusions from field studies to conditions that have not been tested.

In this context, the objective of this part of the study is outlined in the following:

- To validate the Yield-Stress model for wheat yield data at two sites in Egypt
- To predict the changes in yield of wheat and other primary crops (cotton, soybean, clover, faba bean, and onion) under deficit irrigation practices where the crops are irrigated with smaller amounts of water than their full irrigation requirements
- To decide on the most appropriate irrigation regimes to be implemented for the various crops, which save water and, at the same time, maintain satisfactory crop production without any notable yield losses
- To test the capability of the Yield-Stress model in irrigation scheduling.

The findings of this research can be summarized as follows:

- Based on the comparative analysis between the measured and predicted yield data of the crops investigated under varying degrees of water stress, we conclude that the Yield-Stress model can adequately predict yield reductions. The model can provide useful insights into the design of different irrigation treatments. The ease of implementation of the model can help in the wider use of the deficit irrigation technique and help achieve a saving of water in the agriculture sector. The results of the model validation under full irrigation volumes and under deficit irrigation treatments give a clear cut answer confirming the model’s appropriateness in predicting yields and investigating the degree of tolerance of crops to water-stress. Furthermore, the results also suggest that the model can be used in irrigation scheduling to conserve irrigation water with almost no reduction in yield.

- For all the crops investigated, the deficit irrigation technique was practiced successfully. This leads to the conclusion that the crops under investigation can be grown successfully without any appreciable losses in yield using less water than is currently the case. However, the point that needs to be clarified is the extent to which the water supplied can be reduced without resulting in harmful effects on the crop yield.
- The crops under investigations vary greatly in their degree of tolerance to water- stress.
- Cotton was the crop among those studied which can be produced successfully using 30% less water than that corresponding to full irrigation.
- Wheat can be produced successfully using up to 20% less water without any deterioration in the yield. This was also the case for onion. Both wheat and onion could be considered as crops moderately tolerant to water-stress.
- The situation with the other crops investigated was to the contrary. Faba bean is shown to be an intermediate crop where up to 15% of the total amount of water applied could be saved without any significant losses in the yield. Soybean and clover are the poorest among the crops studied in tolerating stress conditions. Both can be safely grown under irrigation with just 10% less water than that required for full irrigation.
- The crops investigated can be classified according to their tolerance to water stress, using the yield under varying degrees of water stress as an indicator, as indicated in Table 4.42.

Table 4.42. Classification of investigated crops according to their degree of tolerance to water-stress.

Crop	Water stress degree	Water saving(%)
Cotton	Highly tolerant	30%
Wheat Onion	Tolerant	20%
Faba bean	Intermediate semi-tolerant	15%
Clover Soybean	Sensitive less tolerant	10%

In spite of the variations in the resistance to water-stress conditions of the crops investigated, generally all of them can be produced successfully and safely with less volumes of water than those that are traditionally used for irrigation. In other words, it can be concluded that there is a high potential for water saving in the irrigation sector by increasing crop water productivity and producing more with less water.

One of the promising options for meeting the gradually increasing water demand, given the limited and fragile nature of the water supply, is to introduce water of known quality and drainage water as supplementary irrigation water sources. Nowadays, it is the policy of the government to fully use drainage water in irrigation to increase, on the one hand, the water allocated to agriculture and, on the other, to save a relatively high volume of freshwater to compensate for increasing water shortages in the other sectors that use water.

The challenge for the future will be to maintain, or even increase, water productivity using less water or by using water of low quality.

4.5 References

Allen, R.G., L.S. Pererira, D. Raes and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper No. 56. FAO, Rome.

Bresler, E. 1987. Application of conceptual model to irrigation water requirement and salt tolerance of crops. Soil Science Society of America Journal. 51:788–793.

Childs, S.W. and R.J. Hanks. 1975. Model of soil salinity effects in crop growth. Soil Science Society of America Proceedings 39:112–115.

de Wit, C.T. 1958. Transpiration and crop yield. Versl. Landbouwk. Onderz. 64.6 Institute of Biology and Chemistry Research on Field Crops and Herbage, Wageningen, Netherlands.

El-Mesiry, T., E.F Abdallh, M.S. Gaballah and S.A. Ouda. 2007. Using Yield-Stress model in irrigation management for wheat grown under saline conditions. Australian Journal of Basic and Applied Sciences 1(4): 600-609.

Food and Agriculture Organizations of the United Nations (FAO). 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. Rome.

Food and Agriculture Organizations of the United Nations (FAO). 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Food and Agriculture Organizations of the United Nations (FAO). 1992. CROPWAT, a computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 26. Rome.

Jamieson, P.D., J.R. Porter, J. Goudriaan, J.T. Ritchie, H. van Keulen and W. Stol. 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. Field Crops Research 55: 23–44.

Loomis, R.S. and W.M. Williams. 1963. Maximum crop productivity: an estimate. Crop Science 3, 67–72.

Khalil, F.A., S.A. Ouda and M.M. Tantawy. 2007. Predicting the effect of optimum irrigation and water stress on yield and water use of barley. Journal of Applied Sciences Research 3(1): 1-6.

Ouda, S.A. 2006. Predicting the effect of water and salinity stresses on wheat yield and water needs. Journal of Applied Sciences Research 2(10): 750-750.

Ouda, S., T. El-Mesiry and M.S. Gaballah. 2007. Using Yield-Stress model to simulate soybean yield reduction under imposing water stress. Research Journal of Agricultural and Biological Sciences 3(6): 827-834.

Ouda, S., A.F. Khalil, R. Abou Elenin, M.A.K. Shreif, B. Benli and M. Qadir. 2008a. Using Yield-Stress model in irrigation management for wheat grown in Egypt. Journal of Applied Biological Sciences 2 (1): 57-65.

Ouda, S. A., S. A. Mohamed and F. A., Khalil. 2008b. Modeling the effect of different stress conditions on maize productivity using Yield-Stress model. International Journal of Natural and Engineering Sciences 2(1): 57-62.

Ouda, S., R. Abou Elenin, M. A. K. Shreif, B. Benli and M. Qadir. 2008c. Prediction of soybean yield and water productivity under deficit irrigation using Yield-Stress model. International Journal of Natural and Engineering Sciences Accepted for publication.

Shani, U. and. L.M. Dudley. 2001. Field studies of crop response to water and salt stress. Soil Science Society of America Journal 65: 1522–1528

Smith, M.D. and L.K. Kivumbi Heng. 2000. Use of the FAO CROPWAT model in deficit irrigation studies. Deficit Irrigation Practices 22: 17-27.

Tantawy, M.M., S.A. Ouda and F.A. Khalil. 2007. Irrigation optimization for different sesame varieties grown under water stress conditions. Journal of Applied Sciences Research 3(1): 7-12.

Toda, O., K. Yoshida, S. Hiroaki, H. Katsuhiro and H. Tanji. 2005. Estimation of irrigation water using CROPWAT model at Km35 project site, in Savannakhet, Lao PDR. Paper presented at the International Symposium on ‘The role of water sciences in Transboundary River Basin Management’, March 10-12, 2005, Ubon Ratchathani, Thailand.

Willmott, C.J. 1981. On the validation of models. Physical Geography 2: 184–194.