Journal of Indian Water Resources Society,
Vol 35, No.1, January, 2015

IRRIGATION SCHEDULING STRATEGIES FOR COTTON CROP IN SEMI - ARID CLIMATE USING WEAP MODEL

Gopal H. Bhatti[1] and H. M. Patel[2]

ABSTRACT

There is constant competing demand for water amongst agricultural, industrial and domestic users as it is fixed and limited resource. With limited availability of irrigation water in arid and semi arid regions it has become necessary to optimize water use efficiency and maximize crop yields under deficit irrigation conditions. Water shortage during the growth period has an impact on ultimate yields. There is need to adopt such irrigation scheduling techniques by which it is possible to have more effective and optimal use of limited supplies of water. Regulated deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. Cotton crop has been taken for case study to simulate the response to deficit irrigation during flowering stage and boll formation stage. A case study was taken to investigate water stress induced during flowering stage and boll formation phase by withholding irrigation by 10days. The simulations for case study indicate that regulated deficit irrigation is resulting in marginal reduction in yield while there is significant increase in irrigation water use efficiency (IWUE) in comparison to conventional practices. Saving of water can be achieved by determining irrigation requirements in real time by using WEAP model incorporating MABIA method.

Keywords: *Dual crop coefficient, Evapotranspiration, Deficit irrigation, Soil moisture balance, WEAP model*

INTRODUCTION

Contribution of irrigated agriculture towards food security has been tremendous which has led to increase of irrigated areas over the last half century. Simultaneously the increase in demand for drinking water and industrial use has resulted in steady decrease of allocation for agriculture. Lot of constraints has slowed down the future irrigation development. Serious water shortages have been reported from many arid and semi-arid regions. Water dependency is serious constraint for further progress. Thus, the challenges of these days are to increase water productivity with dwindling water resources for the growing population, with the greater efficiency of water use for rain fed and irrigated agriculture. Rather than conservation of scarce water resources, the farmers have a tendency to over-irrigate. In order to expand irrigated areas with limited available irrigation water, utmost priority is to optimize irrigation water use efficiency (IWUE) to maximize crop yields. Thus, there is a need to adopt such irrigation scheduling techniques by which it is possible to have more effective and rational use of limited supplies of water. Various agronomic measure such as mulching, anti transpirants, varying tillage practices and regulated deficit irrigation practices can reduce demand for irrigation water (Kirda, 2002).

Cotton is an important fibre crop which is mostly rainfed, except in regions with low annual rainfall where the crop is grown under irrigated conditions in India. Usually no irrigation is required during rainy season until and unless rainfall is very erratic. The Kharif cotton crop is usually rainfed and sown in second week of June with the onset of monsoon while summer crop is sown in second week of May. The seasonal length of crop varies from 150-195 days. The followed traditional practices are to give 2 or 3 irrigations post one month of monsoon of 80mm or irrigation as per the crop water requirement. Depending on the variety and the environmental conditions, bud formation takes about 50-60 days from sowing, around 25-30 days for flower formation and around 50-60 days from flowering to maturity. To ensure good germination pre planting irrigation is important if good rainfall has not occurred. Cotton requires adequate crop water prior to budding and during bud formation. Severe water deficits during flowering may restrict the growth, but with subsequent water application the crop growth recovers. During flowering SMD of about 70% could be tolerated without adversely affecting the yield. Cotton shows multifaceted responses due to its deep root system and has an ability to get conditioned to deficit irrigation. Deficit irrigation imposed during flowering and boll formation for cotton provides acceptable and feasible irrigation options with minimal yield reduction Kirda (2002). Thomas et al. (1976) demonstrated that cotton plants which suffered a slight water stress during vegetative stage adapted themselves and showed higher tolerance of water deficit at later stages. Grimes and Yamada (1982) observed that water stress during vegetative growth causing leaf water potential value less than critical midday value could adversely affect the final yield.

In this study simulation is carried out using WEAP model for irrigated area of Sardar Sarovar Project Region I Block 9A1. The data related to soil, irrigation and climate are obtained from various agencies. The main objectives are as follows: (1) To determine crop water requirement of cotton by simulation using WEAP model in study area. (2) Elucidate the effects of different irrigation strategies on crop yield, WUE and IWUE. (3)To evaluate five different irrigation scheduling strategies (i) Conventional, (ii) Stress imposed of 10 days during starting of flowering stage (iii) Stress imposed of 10 days during starting of boll formation stage (iv) Stress allowed during vegetative stage, afterwards maintaining moisture within readily available moisture with help of model and (v) Model specified irrigation to maintain moisture within readily available moisture for entire crop period.

WATER STRESS EFFECTS ON PLANTS

The highest productivity can be achieved with optimum water supply. The water stress affects the crop growth and productivity. Several crops respond differently, according to degrees of drought tolerance during period of water stress, while certain crops get accustomed to water stress conditions

1. *Research Scholar and Associate Professor, Civil Engineering Department, Faculty of Tech. & Engg., The M.S. University of Baroda, Vadodara 390001.*
Email: gbhatti@gmail.com

2. *Professor, Civil Engg. Deptt., The M.S. University of Baroda, Vadodara 390001.*
Email: haresh_patel@yahoo.com

Manuscript No.: 1368

under limited water supply and have better yields even with less water. Precise knowledge of crop response to water is must as drought tolerance varies as per growth stage and crop species (Doorenbos and Kasam, 1979).

Smith et al. (2002) reported that the water stress results in less evapotranspiration by closure of the stomata thereby reduced absorption of carbon and decreased biomass production. The reduced biomass production has little effect on ultimate yields. Water stress applied during reproductive growth can hamper fruit or grain, resulting in decreased yields. Studies indicate that plants may shed tillers, lose leaves, or abort flowers and seeds when stress develops. If water stress is allowed to develop early in any growth stage, irreparable damage to the yield occur leading to sub- optimal yields for a given level of water use (Stegman, 1983). In some cases water stress may trigger physiological processes that actually increase yield such as (i) Increase root development by penetrating to deeper soil layers. (ii) Early ripening of grains (iii) Improved quality and flavor of fruits e.g. sugarcane, grapes etc. and (iv) Inducing flowering in case of cotton (Kirda, 2002). Water stress affects the lengths of individual crop growth stages and therein has a significant effect on crop phenology. It is a well known fact that water stress hastens flowering and physiological maturity. Water stress in the vegetative period leads to changes in rooting density and depth; the depletion factor p for the next stage can be influenced due to this reason. In some crops, water stress can have positive effect on the quality of produce (Kassam and Smith, 2001).

DEFICIT IRRIGATION PRACTICE

Different irrigation strategies, soils and irrigation systems would require different amounts of irrigation to produce maximum ET and yield (Martin et al., 1984). The best use of irrigation water would be that all water is utilized by the crop for evapotranspiration. An optimal yield is usually obtained with maximum actual evapotranspiration ET_a with high level of crop water availability. Irrigating to achieve maximum yield and consequently crop evapotranspiration ET_c is not the most efficient use of irrigation water**.** If the water supply is adequate, irrigation scheduling can be monitored such that the soil moisture content is maintained through-out the seasons in the roots zone depth at levels which do not hamper the crop growth. Any restriction in supply of water is likely to induce a decrease in crop yield. Water deficits are unavoidable in some periods of the growing season when available supply is limited. Irrigation scheduling becomes difficult because irrigation decisions need to be decided on the crops sensitivity to water deficits in different periods of its growth. It is necessary to take into account the stage of growth when plants are most sensitive to water shortage. Each crop has certain stages at which if there is shortage of water, yield is drastically reduced. When there is shortage of water, it is better to take care of critical stages first to obtain increased water use efficiency (Rao et al., 1988).

It requires an evaluation of alternative irrigation schedules and choosing the schedule which maximizes yields for the given level of water supply. Regulated deficit irrigation is one of the options to maximize water use efficiency for higher yields per unit of irrigation water applied. Deficit irrigation practices differ from conventional water supplying practices, wherein supply of water is reduced below maximum level and the crop is exposed to mild level of water stress either during whole growing season or a particular period with minimum effects on yield. It is presumed that the benefits achieved through diverting the saved water to irrigate other crops are quite significant in comparison to any yield reduction. It is possible to identify irrigation scheduling strategies that minimize water supply with meager impacts on crop quality and yields. Deficit irrigation applied either throughout the growing season or at pre determined growth stages are well suited for crops such as cotton, maize, wheat, sunflower, sugar beet and potato. Moreover regulated deficit irrigation imposed during flowering and boll formation stages in cotton will provide acceptable and feasible irrigation options with minimum yield reductions with limited supplies of irrigation water (Kirda, 2002). In cotton, the period from flowering to yield formation (flowering, bud formation and boll formation) is critical with respect to water deficits (Shreder et al., 1977; Laktaev, 1978; Domullodjanov, 1983). On analyzing several deficit irrigation strategies for cotton in water scarce region, the adoption of high water deficit that produce high water savings would lead to yield losses that may not be acceptable and hence concluded that relative mild deficits may be adopted (Pereira et al., 2009). The growth period from crop establishment to flowering is sensitive to excess water and may induce excessive vegetative growth. Several studies show that cotton yields are reduced by excessive water applications (Jackson and Tilt, 1968; Grimes et al., 1969).

If good management practices are ensured higher water use efficiency can be achieved with deficit irrigation for crops that are less sensitive to stress such as cotton, maize, wheat, sunflower, sugar beet. Water use efficiency (WUE) can be achieved 1.2 times more than that under conventional irrigation practices with a 25 percent deficit for certain crops such as common bean, groundnut, soybean and sugarcane where reduced evapotranspiration is limited to (a) certain growth stage(s) (Kirda, 2002).

Many computer programs related to soil moisture are available which help to decide whether to irrigate or not according to pedological, agricultural and meteorological parameters. Nowadays, it is possible to monitor soil moisture status in varied soils using soil moisture neutron probes (SMNP) sets of tensiometers for crops that are subjected to deficit irrigation (Moutonnet, 2002). In fine textured soil, plants may prolong water stress under deficit irrigation practices and will be more booming rather than in sandy soil where plants may undergo water stress quickly. Thus it is utmost necessary to consider the water retention capacity of the soil before inducing water stress. Various water balance models have been developed based on well recognized methodologies for determination of crop evapotranspiration and yield responses to water with simulation of crop water stress conditions and computation of yield reductions (FAO, 1998; FAO, 1979). CROPWAT model (FAO, 1992) is widely used for this purpose which uses single crop coefficient. WEAP model has incorporated MABIA method which provides daily simulation of transpiration, evaporation, irrigation requirements and scheduling, crop growth and yields, and includes modules for estimating reference evapotranspiration and soil water capacity. It uses dual K_c method as described in FAO-56. MABIA is an improvement over CROPWAT which uses dual crop coefficient approach separating evaporation and transpiration (Sieber and Purkey, 2011).The dual crop coefficient approach (K_{cb} + K_e) gives a better estimation of daily crop evapotranspiration because it separately considers soil evaporation and crop transpiration. This approach allows one to plan irrigation schedules properly, especially in the case of crops that do not completely cover the soil, where evaporation from the soil surface may be substantial (Rossa et al., 2012).

MATERIALS AND METHODS

Crop evapotranspiration can be computed by multiplying reference crop evapotranspiration to crop coefficient. The reference crop evapotranspiration can be estimated by many methods. The FAO Penman-Monteith method is recommended as sole standard method for the definition and computation of the reference evapotranspiration (Allen et al., 1998).

Dual Crop Coefficient Approach

The effect of crop characteristics differentiating a field crop from the reference crop (grass) is integrated with help of crop coefficient K_c value. There are two approaches to determine the crop coefficient K_c. (1) Single Crop Coefficient (2) Dual Crop Coefficient (Allen et al., 1998).

The difference in evapotranspiration between the field crop and reference grass surface is expressed by the crop coefficient. The difference can be incorporated into one single coefficient or it can be broken up into two factors describing separately the difference in evaporation and transpiration between both surfaces. In single crop coefficient approach, the effects of soil evaporation and crop evapotranspiration are combined into one K_c coefficient. Dual crop coefficient approach calculates the actual increase in K_c for each day as a function of plant development and the wetness of the soil surface. Further, the effects of soil evaporation and crop evapotranspiration are calculated separately. Instead of one coefficient, it uses two coefficients. (1) Basal crop coefficient which describes crop transpiration. (2) Soil water evaporation coefficient; describes the soil water evaporation from the soil surface (Allen et al., 1998).

The single crop coefficient K_c is substituted by the following equation:

$$K_c = K_{cb} + K_e \tag{1}$$

The basal crop coefficient K_{cb} is defined as the ratio of Crop evapotranspiration ET_c to Reference Evapotranspiration ET_o; it represents the condition when soil surface layer is dry but average soil moisture content in the root zone is sufficient to support full transpiration of plant. The soil water evaporation coefficient K_e, determines the soil water evaporation from soil surface. When soil is wet, following rain or irrigation the value of K_e is large. The value of K_e diminishes and reaches zero when no water is left for evaporation as the soil surface dries subsequently. In no case, the sum of K_{cb} and K_e should exceed the maximum value, K_c max; which is decided by the energy available for the evapotranspiration at the soil surface. Due to more complexities involved than the one time averaged K_c coefficient (i.e. single crop coefficient) the dual coefficient approach is best suited for research studies, real time irrigation scheduling, and for soil moisture balance computations; where daily variations in soil surface wetness, soil moisture profile, and continuous changing deep percolation, play a vital role (Allen et al., 1998; Rossa et al., 2012; Bhatti et al., 2012). The selection of the approach primarily depends upon the availability of climatic data, accuracy required and the purpose of the calculation. The dual crop coefficient is adopted in this study and crop evapotranspiration is computed under standard conditions (ET_c) and non standard conditions (ET_{cadj} or ET_a).

Water stress coefficient (K_s)

The effect of soil water stress is incorporated by multiplying the crop coefficient by the water stress coefficient K_s. Crop evapotranspiration computed using the dual crop coefficient approach is denoted as $ET_a = (K_s * K_{cb} + K_e) * ET_o$

Where there is no soil water stress, Ks = 1 while, for soil water limiting conditions, Ks < 1.

To avoid crop water stress irrigation is needed to be applied. The K_s value can be calculated as mentioned below (Allen et al., 1998; Allen R.G., 2002). :

$$K_s = (TAW - D_r)/(TAW - RAW) \tag{2}$$

Where TAW = total available water in mm, D_r = root zone depletion in mm, RAW= readily available water in mm. Water stress coefficient K_s value maximizes when soil is wet, and evapotranspiration occurs at potential rate. The value of K_s equal's unity following rainfall or irrigation. As the soil surface dries, actual evapotranspiration begins to decline below the potential rate $K_s < 1$. When no water is available for evapotranspiration in the top soil then K_s reaches zero. The crop is said to be water stressed when the soil starts drying and potential energy of the soil water drops below a threshold value. In conventional practices, the irrigation is applied before the stress conditions are attained if there is no rainfall. If soil moisture deficit exist and there is substantial rainfall, the moisture is retained near the soil surface; this is most obvious when the soil has an appreciable clay content. After significant rainfall the soil remains moist near the ground surface and crop continue to revive for several days. The value of soil moisture depletion (SMD) with respect to total evaporable water (TEW), total available water (TAW), readily evaporable water (REW), and readily available water (RAW) can be classified in three situations.

(1) $REW/RAW \geq SMD$ The crop will have potential evaporation and evapotranspiration.

(2) $TEW/TAW > SMD \geq REW/RAW$ The crop will have reduced evaporation and evapotranspiration.

(3) $SMD > TEW/TAW$ The crop will have no evaporation and no evapotranspiration.

The distribution of moisture in the soil is not so important in the first situation, since the actual evapotranspiration equals the potential value. In situation (2) and (3), crop stress coefficient (K_s) and evaporation coefficient (K_e) are required to be introduced for consideration of reduced soil moisture(Rushton et al., 2005). To avoid crop water stress, irrigation needs to be applied before or at the moment when readily available water RAW is equal or greater than soil moisture depletion SMD i.e. SMD < RAW. However, management induced soil water stress may be initiated in different growth stages for crops like cotton, sugar beet, coffee etc. to have better yield (FAO, 1998).

Crop yield response factor (K_y)

Mannocchi and Mecarelli (1994) stated it was feasible to model relationship between crop yield and water applied by using crop yield response factor equation. Before implementing deficit irrigation, it is necessary to know crop yields response to water stress, either during defined growth stages or throughout the whole season (Kirda, 2002). Crop response factor is useful indicator for the sensitivity and crop tolerance to water stress during the whole season and/or crop growth stage. Crop response factor estimates relative yield reductions based on the measured reduction in crop transpiration (Moutonnet, 2002). The crop yield response factor K_y varies depending on species, variety, irrigation method and management, and growth stage when deficit evapotranspiration is imposed. The equation is denoted as follows

$$K_y = \frac{\left[1-\frac{Y_a}{Y_m}\right]}{\left[1-\frac{ET_a}{ET_c}\right]} \quad (3)$$

$$Y_a = Y_m[1 - K_y\left(1 - \frac{ET_a}{ET_c}\right)] \quad (4)$$

Where, Y_a and Y_m are actual and maximum crop yields corresponding to actual evapotranspiration ET_a and maximum evapotranspiration ET_c. If a crop response factor is greater than unity, it indicates that the relative yield decrease for a given ET deficit is proportionately greater than the relative decrease in ET. Thus as crop yield response factor (K_y) increases water use efficiency (E_c) decreases which implies that benefit from deficit irrigation is unlikely in case of K_y greater than unity. Significant savings in irrigation water through deficit irrigation can be obtained when the crop yield response factor (K_y) is less than 1 during the entire season or growth stage (Kirda et al., 1999a).

The Equation of water use efficiency (E_c) is given as follows.

$$E_c = \frac{Y}{ET_a} = \left[K_y - \frac{K_y - 1}{ET_a/ET_c}\right] \times \frac{Y_m}{ET_c} \quad (5)$$

Water use efficiency (WUE) is computed as yield of crop per actual evapotranspiration. The maximum water use efficiency (WUE) tends to occur at maximum ET (ET_c). Irrigation water use efficiency (IWUE) is yield per irrigation water applied; highest IWUE usually occurs at an evapotranspiration generally less than maximum evapotranspiration ET_c. Declines in IWUE with increasing irrigation are usually associated with soil water storage, drainage, excessive soil water evaporation, and runoff or if water deficit occurs at a critical growth stage (Howell et al., 1990). Tolk et al., (2003) observed that generally IWUE declined with increasing irrigation application but was variable in some irrigation treatments, due to water stress at critical growth stages. Further, no differences among soil types occurred in IWUE in either year. Howell (1995) showed that both max WUE and IWUE occurred at or near $ET_{c,}$ which had high rainfall and somewhat cooler season than normal. But, when the climate was more typical of the region, both maximum WUE and IWUE occurred at an ET considerably less than ET_c.

Large numbers of computer models are available for computing the soil water balance and generating improved irrigation schedules. These models are right tools for developing and evaluating irrigation strategies. The WEAP-MABIA computer program can be used for this purpose to compute ET_a and soil moisture balance on daily basis (Sieber and Purkey, 2011; Choksi et al., 2012). A daily water balance, expressed in terms of depletion at the end of the day, is:

$$D_{r,i} = D_{r,i-1} - P_i + SR_i - I_i - CR_i + ET_{a,i} + DP_i \quad (6)$$

Where $D_{r,i}$ = root zone depletion at the end of day i [mm], $D_{r,i-1}$ = depletion in the root zone at the end of the previous day, i_{-1} [mm], P_i = precipitation on day i [mm], limited by maximum daily infiltration rate [mm], SR_i = surface runoff from the soil surface on day i [mm], I_i = net irrigation depth on day i that infiltrates the soil [mm], CR_i = capillary rise from the groundwater table on day i [mm], $ET_{a,i}$ = actual crop evapotranspiration on day i [mm], DP_i = water flux out of the root zone by deep percolation on day i [mm] .

The daily moisture balance equation (6) enables the user to simulate various irrigation scenarios and estimate yield reductions if any.

CASE STUDY

The Sardar Sarovar Project (SSP) being one of the biggest multipurpose projects of India irrigating 1.8 million hectare in Gujarat, 75,000 hectare in Rajasthan and 37,500 hectare in Maharashtra the three major states of the country. The SSP command area phase – I; lies between 21^0-15'to 22^0 –53' N latitudes and 72^0–31' to 73^0 – 43' E longitudes. The study area covers Block 9A1 of Vadodara district of SSP. The climate of area is semi arid; the rainfall is erratic and non uniform. The average 15 years rainfall has been found to increase by 32% while the number of rainy days has declined from fifty three days per year (1936-1950) to forty two days per year (1995-2010). The intensity of very heavy rainfall in 24 hrs has almost doubled from seven days to sixteen days during the aforesaid period. The major crops grown in this area are cotton, pigeon pea, wheat, jowar etc. The cotton crop grown in the region is taken for study purpose. Sandy clay loam soil is prevalent in the area having soil saturation- 33.00%, field capacity-25.13%, wilting point- 12.16% and available water capacity 12.97%. Generally the natural surface drainage system is well developed in this region. Prickett and Longuist (1971) mathematical modeling studies stated that over irrigation in the study area could result in water logging. Scenarios without conjunctive use demonstrated that surface irrigation applications up to about 500 mm per year could lead to significant water logging problem. Area, probable to get water logged by the end of Kharif season varied between 25 to 38 per cent of the GCA, which could be largely brought down if ground water abstraction to the extent of 200 MCM was initiated from the 7^{th} year onwards (Pathak, 1989). Hence evaluation of irrigation strategies is very much required.

Data

Cotton crop is sown on 22^{nd} June and harvested on 2^{nd} January. The water year selected for this study begins from 1^{st} June 2003 and ends on 31^{st} May 2004. The soil is considered at its field capacity following precipitation or irrigation therefore, initial depletion is taken as zero. Daily climatic data of precipitation, wind speed, sunshine hours, maximum and minimum temperature and relative humidity of the region is used. Cotton is having total crop growth stage length of 195 days wherein the initial, development, mid-season and late is of 30days, 50days, 60days, and 55days respectively. Basal crop coefficient K_{cb} values of initial, mid season, and late are taken as 0.15, 1.15, and 0.45 respectively while depletion factor is considered 0.65 for all the seasons. The yield response factor K_y for initial, development, mid season, late and overall values selected for the model is 0.40, 0.40, 0.50, 0.40 and 0.85 respectively. The maximum height of the crop, minimum root depth, maximum root depth and maximum yield taken are 1.35m, 0.15m, 1.35m and 2044 kg/hectare respectively. Out of the various strategies available to trigger irrigation the fixed interval, % of RAW and combination of both is employed. The irrigation amount is decided as per the selected options such as fixed depth, % of RAW and combination of both is used. For this study five scenarios are considered. The irrigations of 80mm of water are provided, except for Case IV and Case V as shown in Table 1. Case I depicts the conventional irrigation approach while Case II and Case III are selected to study the effect of deficit irrigation imposed during flowering and boll formation phase. In Case IV no irrigation is applied in vegetative phase and afterwards irrigation strategy is decided by model considering stress free condition throughout the remaining growth. In Case V the irrigation strategy is decided by model considering stress free condition throughout the growth (Table1). For all irrigation schedules, the date of the last irrigation is at least 20 days before harvesting since cotton lint quality is affected when its moisture content at harvest is higher than 8% (Barker, 1982, 1996; Barker and Laird, 1993); thus last date of irrigation was taken 25 to 35 days before harvesting.

ANALYSIS AND DISCUSSION

WEAP model was run for the cotton crop for five cases. The model simulates total yield and soil moisture balance using equation (4) and (6) respectively for all the cases, Water use efficiency (WUE or E_c) and irrigation water use efficiency IWUE are also computed using equation (5) and yield per irrigation water applied respectively. The traditional practices promote deficit irrigation in vegetative stage which was established by studying the Case I where crop faces no water stress in entire period except mild stress during vegetative stage and initial days of flowering. In Case II, Case III water stress is induced during flowering and boll formation phase by withholding irrigation by 10days respectively. In Case IV no stress is allowed after vegetative phase and crop is irrigated immediately as soil moisture depletion reaches as specified by model. In Case V no stress is allowed throughout the growth period. The variations in soil moisture depletion for all Cases are shown in Fig. 1. ET_a are low by 28mm, 54mm, 47mm and

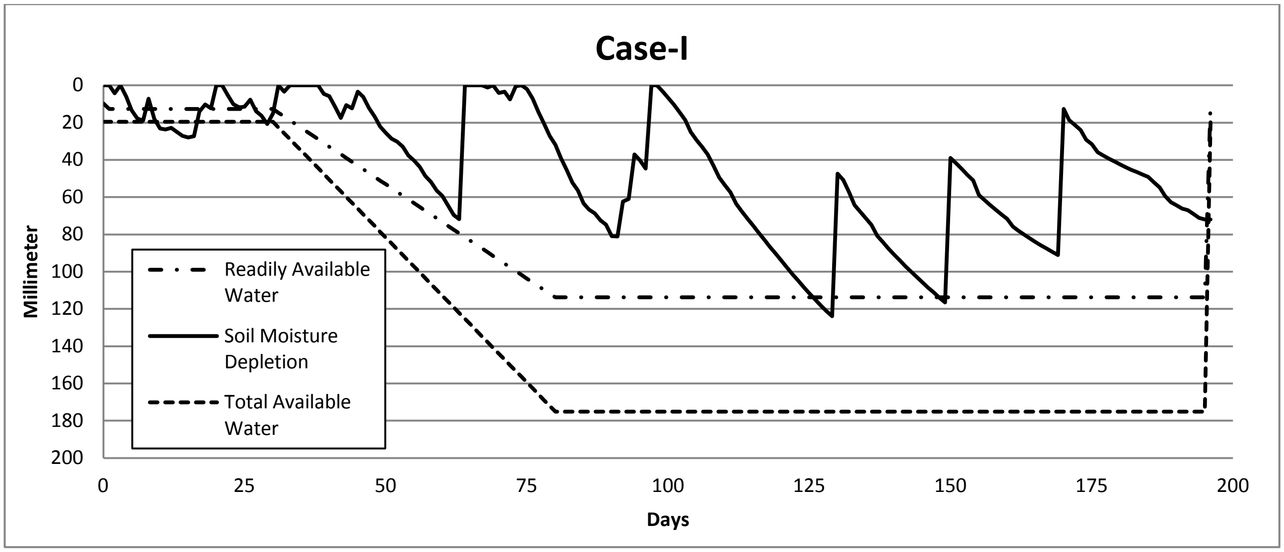
Table1: Irrigation Strategy for five cases Cotton Crop.

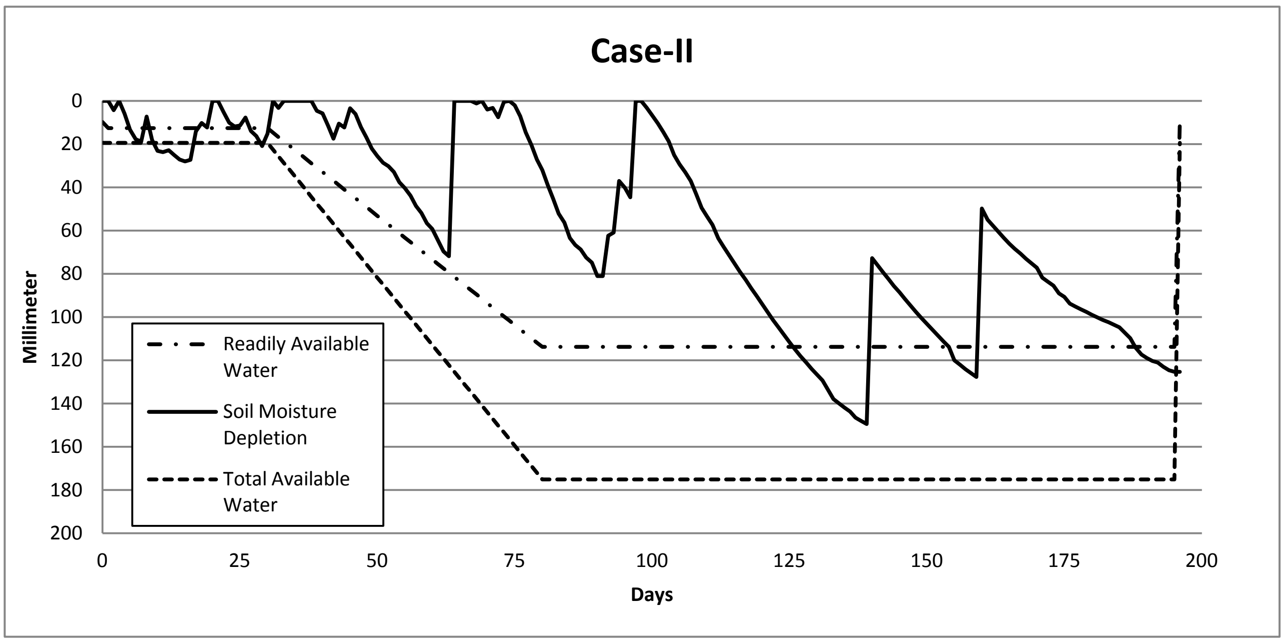
Case	Irrigation Strategy		
	Irrigation Scheduling*	**Irrigation Amount mm**	**Remarks**
I	130, 150, 170	80	Irrigations as per traditional practices at fixed interval of 20 days post one month of offset of monsoon.
II	140, 160	80	Stress imposed during flowering phase; irrigation withheld for ten days starting at 130 days after sowing.
III	130,160	80	Stress imposed during boll formation phase; irrigation withheld for ten days starting at 150 days after sowing, followed by one irrigation
IV	125,160	115 and 116 Varying	No irrigation in first month, Afterwards Irrigated when depletion is 100% RAW and amount of irrigation is 100% of SMD
V	4,6,9,13,26,125,&160	13,14,18,17,14,115 & 116	No stress allowance ; Irrigated when depletion is 100% RAW and amount of irrigation is 100% of SMD

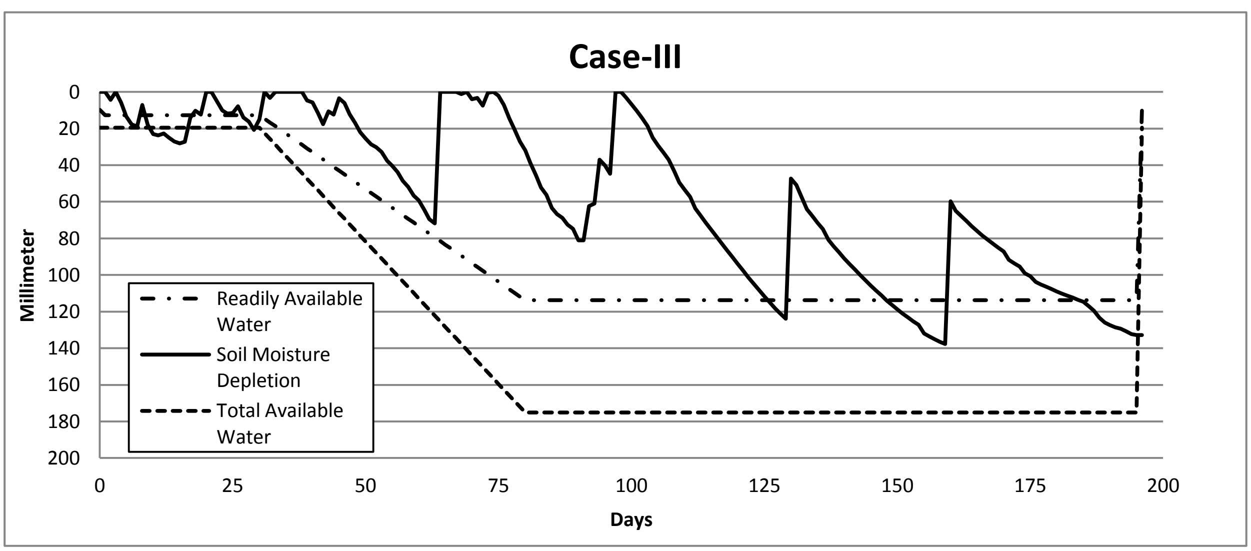
***** From date of sowing.

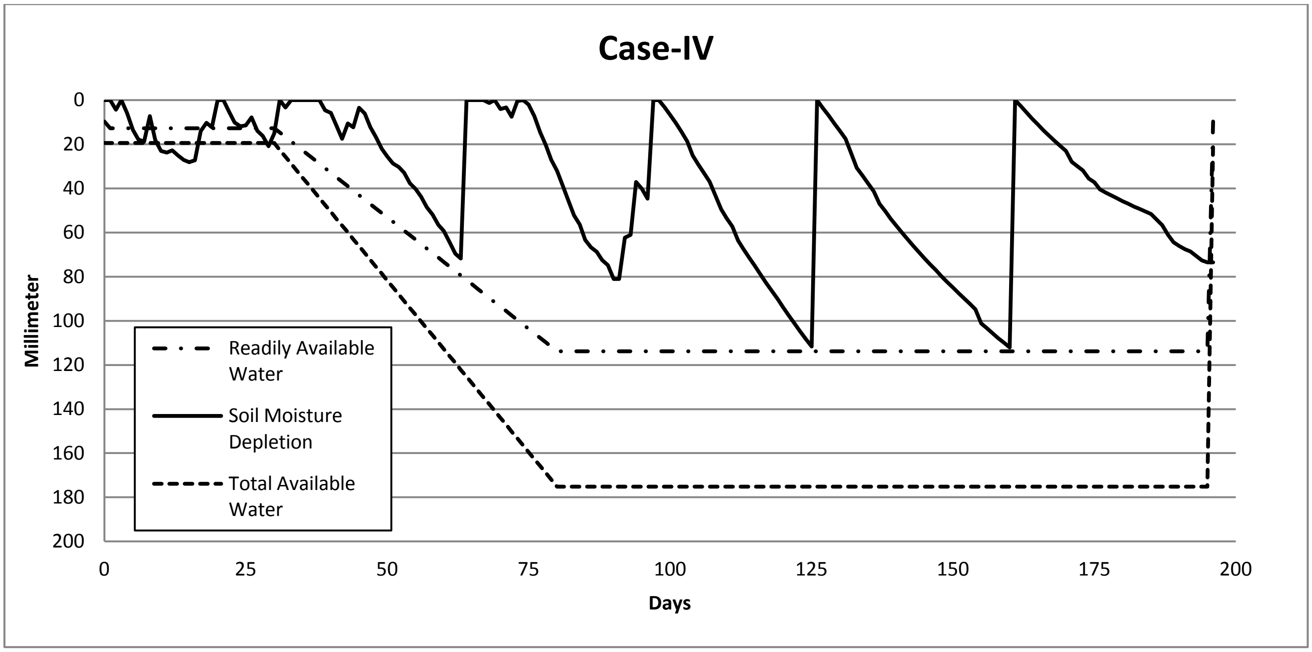
T**able 2: Yield, WUE, IWUE and Soil moisture balance, for Cotton crop for five different cases of Irrigation.**

Case	**ETc mm**	**Actual**			**Irrigation mm**	**Rain fall mm**	**Run off mm**	**Flow to GW. mm**	**Soil moisture storage mm**	**Yield Kg/ha**	**WUE E_c**	**IWUE**
		Evap. mm	Trans. mm	ET_a mm								
I	731	214	506	720	240	899	179	312	72	1951	2.71	8.13
II	724	207	486	694	160	899	179	312	126	1859	2.68	11.62
III	721	205	496	701	160	899	179	312	133	1891	2.70	11.82
IV	722	206	507	712	231	899	179	312	73	1958	2.75	8.48
V	748	232	516	748	307	899	192	340	73	2044	2.73	6.66


Case-I
Millimeter
Days
0
20
40
60
80
100
120
140
160
180
200
0
25
50
75
100
125
150
175
200
Readily Available Water
Soil Moisture Depletion
Total Available Water


Case-II
Millimeter
Days
0
20
40
60
80
100
120
140
160
180
200
0
25
50
75
100
125
150
175
200
Readily Available Water
Soil Moisture Depletion
Total Available Water


Case-III
Millimeter
Days
0
20
40
60
80
100
120
140
160
180
200
0
25
50
75
100
125
150
175
200
Readily Available Water
Soil Moisture Depletion
Total Available Water



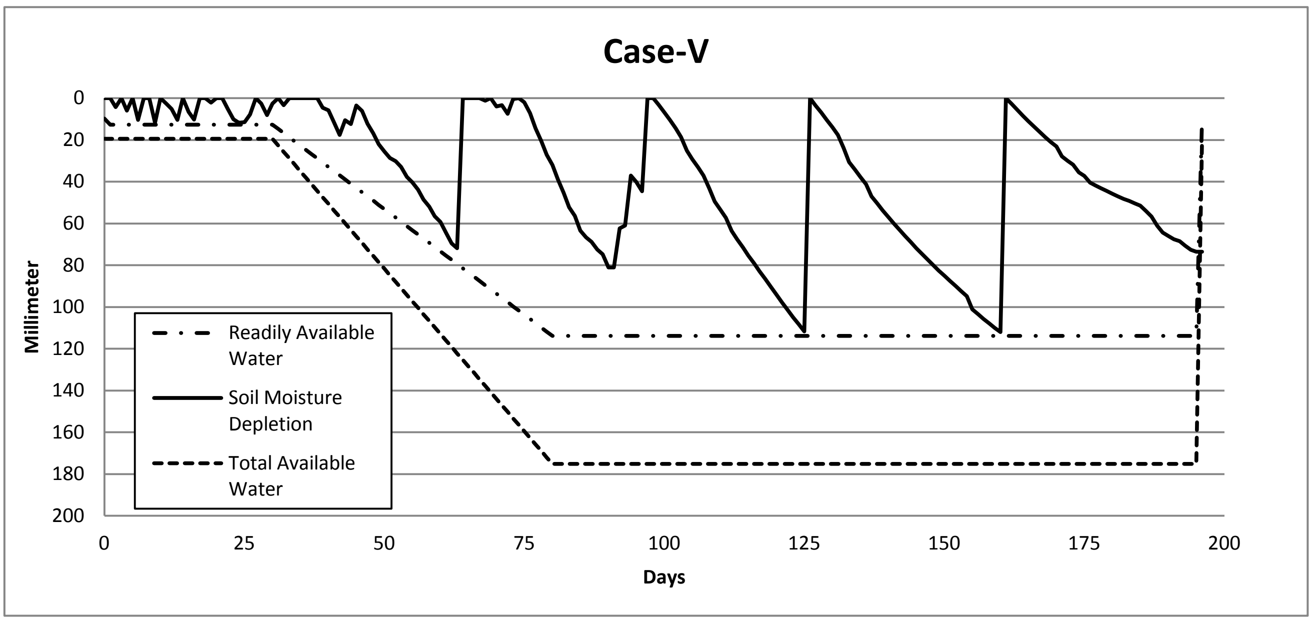


Fig. 1: Soil Moisture Balance in Case I, II, III, IV and V

36mm than the ET_C except Case V where the crop transpires at potential rate. In Case V, 13mm and 28mm more amount of water is lost in form of surface flow and ground water flow. It is observed that Case I - IV is having yield reduction of 5%, 9%, 7% and 4% respectively in comparison with Case V. The WUE reduces very slightly for all cases except in Case IV where increase is observed compared to Case V. The IWUE is found to increase noticeably in Case II and Case III compared to Case V due to decrease in one irrigation of 80mm depth. The variation of Evapotranspiration, Evaporation, Transpiration, Yield, WUE, IWUE, Run off and Flow to Ground Water in selected water year is shown in the Table 2.

We have considered Case V over here for the purpose of comparing the WUE, IWUE and yield with other irrigation scenarios. In Case V we envisage to have no water stress condition thus irrigation is given to the Cotton crop when 100 percent of readily available water (RAW) soil moisture depletion is attained. The amount of irrigation is equivalent to 100% percent soil moisture depletion as per model based i.e. Case V.

As the model based irrigation is directly affected by availability of water due to rainfall and very appreciable rainfall has been observed during the water year under consideration, the resulting value of irrigated water is on lower side. The amount of irrigation given in Case V is 307 mm which is 67 mm, 147mm, 147mm and 76mm greater than Case I- Case IV respectively. Minor reduction of transpiration for Case I- Case IV (10mm, 30mm, 20mm, and 9mm) is noticed in comparison to Case V. There is significant increase in yield in Case V while no significant change is noticed in WUE in comparison to the Case I to Case IV.

CONCLUSION

Actual evapotranspiration is determined using Penman Monteith Method and dual crop coefficient approach using MABIA which is incorporated in the WEAP model. Conventional irrigation strategy (Case-I), Irrigation strategy with mild water stress imposed in flowering and boll formation (Case II and Case III), Irrigation strategy with no stress allowed except vegetative stage (Case IV) and Model determined irrigation strategy (Case-V) have been evaluated and compared for cotton crop. The prevention of water stress condition by model application improves yield of crop. FAO-56 Penman Monteith model is found very useful to precisely estimate daily potential evapotranspiration using daily climatological data. The dual crop coefficient approach helps in computing separately soil evaporation and transpiration under normal and water stress condition. Mild water stress applied in cotton crop during flowering (Case II) and boll formation phase (Case III) reduce the yield 4.7% and 3% respectively while significant increase in IWUE of 42% and 45% is noted when compared with traditional practices. No significant affect is noticed in WUE amongst all the cases.

ACKNOWLEDGEMENT

The authors wish to acknowledge the data support extended by Sardar Sarovar Narmada Nigam limited, Vadodara and State Water Data Centre, Gandhinagar, Gujarat, India. The authors are also thankful to WEAP developers for providing software and support for this study.

REFERENCES

1. *Allen, R. (2002). Evapotranspiration: The FAO 56 Dual Crop Coefficient Method and Accuracy of predictions for Project - wide Evapotranspiration. International meeting on Advances in Drip/Micro Irrigation.*
2. *Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage paper 56. Rome: United Nations Food and Agriculture Organization.*
3. *Barker, G. L. (1982). Equation for estimating cotton preharvest losses. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water management 96 (2009), 723-735.*
4. *Barker, G. L. (1996). Equilibrium moisture content of cotton plant components. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*
5. *Barker, G. L., & Laird, J. W. (1993). Drying and humidification rates for cotton lint. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*
6. *Bhatti, G. H., & Patel, H. M. (2012). Estimation of evapotranspiration for four major crops using dual crop coeffcient method in Sardar Sarovar command area. Hydro - 2012, Confernece on Hydraulics, Water Resources, Coastal and Environmental Engineering. Mumbai: Indian Institute of Technology.*
7. *Chokshi, R. K., Bhatti, G. H., & Patel, H. M. (2012). Estimation of Evapo-transpiration in Sardar Sarovar Command Area Using WEAP. 2012 International SWAT COnference. Delhi: Indian Institute of Technology.*
8. *Domullodjanov, K. D. (1983). Recommendations for calculating irrgation regimes when programming yields in cotton rotation. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*
9. *Doorenbos, J., & Kassam, A. H. (1979). Yield response to water. Irrigation and Drainage Paper No.33.*
10. *FAO. (1979). Yield response to water. Irrigation and Drainage Paper No. 33.*
11. *FAO. (1992). CROPWAT. Acomputer program for irrigation planning and management. Irrigation and Drainage Paper no. 46.*
12. *FAO. (1998). Crop evapotranspiration; guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. Rome.*
13. *Grimes, D. W., Yamada, H., & Dickens, W. L. (1969). Functions for cotton production from irrigation & nitrogen fertilization variables. I: Yield & ET. In: Pereira, et al... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*
14. *Grimes,D.W.& Yamada,Y.H. (1982). Relation of cotton growth and yield to minimum leaf water potential. Crop Science 22: 134-139*
15. *Howell, T. A., Cuenca, R. H., & Solomon, K. H. (1990). Crop Yield response. In: Tolk, J. A. and Howell T. A. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agricultural Water Management 59 (2003), 97-111.*
16. *Howell, T. A., Yazar, A., Schneider, A. D., Dusek, D. A., & Copeland, K. S. (1995). Yield and water use efficiency of corn in response to LEPA irrigation. In: Tolk J. A., Howell T. A. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agricultural Water Management 59 (2003), 97-111.*
17. *Jackson, E. B., & Tilt, P. A. (1968). Effects of irrigation intensity and nitrogen level on the performance of eight varieties of upland cotton. In: Pereira. et al. Irrigation scheduling strategies for*

cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.

18. *Kassam, A., & Smith, M. (2001). FAO Methodologies on Crop Water Use and Crop Water Productivity. Rome: Expert meeting on Crop Water Use Productivity.*

19. *Kirda, C. (2002). Deficit irrigation scheudling based on plant growth stages showing water stress telerance. Rome: Food and Agriculture Organization of the United Nations.*

20. *Kirda, C., Kanber, R., & Tulucu, K. (1999a). Yield response of cotton, maize, soybean, sugar beet, sunflower and wheat to deficit irrigation. In: Kirda, C. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. Rome: FAO of the United Nations (2002).*

21. *Laktaev, N. (1978). Cotton Irrigation. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*

22. *Mannocchi, F., & Mecarelli, P. (1994). Optimization analysis of defecit irrigation systems. Journal of Irrigation and Drainaage Engineering 120, 484-502.*

23. *Martin, D. L., Watt, D. G., & Gilley, J. R. (1984). Model and production function for irrigation management. In: Tolk, J. A., Howell T. A. Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. Agricultural Water Management 59 (2003), 97-111.*

24. *Moutonnet, P. (2002). Yield response factors of field crops to deficit irrigation. Rome: Food and Agriculture Organization of the United Nations.*

25. *Pathak, M. (1989). Planning for Prosperity. Gandhinagar: Sardar Sarovar Narmada Nigam Ltd.*

26. *Pereira, L. S., Paredes, P., Cholpankulov, E. D., Inchenkova, O. P., Teodoro, P. R., & Horst, M. G. (2009). Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana Valley, Central Asia. Agricultural Water Management 96 , 723- 735.*

27. *Rao, N. H., Sarma, P. B., & Chander, S. (1988). Irrigation Scheduling under a limited water Supply. Agricultural Water Management, 15 , 165-175.*

28. *Rossa, R. D., Paredessa, P., Rodrigues, G. C., Alvesa, I., Fernando, R. M., & Pereirra, L. S. (2012). Implementing the Dual Crop Coefficient approach in interactive software. Journal of Agricultural Water Management, 103, 8 - 24.*

29. *Rushton, K. R., Eilers, V. M., & Carter, R. C. (2006). Improved Soil moisture balance methodology for recharge estimates. Journal of Hydrology 318, 379 - 399.*

30. *Shreder, V. R., Vasiliev, I. K., & Trunova, T. A. (1977). Hydromodule zoning and calculation of irrigation norms for cotton under arid conditions. In: Pereira. L.S., Paredes, P., Cholpankulov, E.D... Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana valley, Central Asia. Agricultural Water Management 96 (2009), 723-735.*

31. *Sieber, J., & Purkey, D. (2011). WEAP 2011 Tutorials and user guide. Stockholm Environment Institute (SEI).*

32. *Smith, M., Kivumbi, D., & Heng, L. K. (2002). Use of the FAO CROPWAT model in deficit irrigation studies. Rome: Food and Agriculture Organization of the United Nations.*

33. *Stegman, E. C. (1983). Irrigation Scheduling applied timing criteria. In: Rao, N. H., Sarma, P.B.S. and Chander, S. Irrigation Scheduling under a Limited Water Supply. Agricultural Water Management 15 (1988), 165-175.*

34. *Thomas, J. C., Brown, K. W. & Jordan, J.R. (1976). Stomatal response to leaf water potential as affected by preconditioning water stress in the field. Agronomy Journal 68 , 706-708.*

35. *Tolk, J. A., & Howell, T. A. (2003). Water use efficiencies of grain sorghum grown in Three USA Southern Great Plains soils. Agricultural Water Management 59 , 97-111.*