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# MODELING DEFICIT IRRIGATION EFFECTS ON MAIZE TO IMPROVE WATER USE EFFICIENCY

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Deficit irrigation practices can save water and increase water use efficiency (WUE). This study was designed to evaluate effects of deficit irrigations, Management Allowed Depletion (MAD) levels, on maize fodder yields. The study was conducted at research area of the Department of Irrigation and Drainage, University of Agriculture, Faisalabad, Pakistan. Treatment effects were significant ($p \leq 5\%$) with T1 (MAD of 30%) producing maximum fodder yield of 8933 kg ha$^{-1}$ while treatment T2 (MAD of 60%) had minimum fodder yield of 7994 kg ha$^{-1}$ with water savings of 25% and water use efficiency (WUE) of 86 kg ha$^{-1}$ mm$^{-1}$. The GLEAMS model was calibrated to simulate the effects of relative management practices on hydrologic parameters. The GLEAMS model predicted runoff, deep percolation, and evapotranspiration reliably having percent difference of less than 5% between predicted and observed data but underestimated soil water contents. The scenario simulation, however, showed that keeping soil water contents within 50 to 90% of available water in root zone had maximum WUE. These results revealed that 2$^{nd}$ and 3$^{rd}$ irrigations were least sensitive and there is potential of water saving and increasing WUE during first quarter of vegetative growth, which can also be investigated for other crops.
**Keywords**: Deficit irrigation, MAD, GLEAMS model, maize, water use efficiency

## INTRODUCTION

Dwindling water resources and growing demand for water have affected its security for irrigation. At the same time, the need to meet the growing demand of food for increasing population will require increased crop production using less water. Achieving better efficiency of water use will be a primary challenge in the near future and will include the employment of techniques and practices that deliver more accurate supply of water to crops. In this context, deficit irrigation can play an important role in increasing water use efficiency (WUE) while considering topographical effects on soil water availability (Moayedi *et al*., 2010; Bakhsh and Kanwar, 2008). Ozbahce and Tari (2010) reported that deficit irrigation with moderate emitter spacing present irrigation strategy, helpful in water scarce regions. Kang *et al.* (2000) have shown that regulated deficit irrigation (RDI) for certain periods during maize growing season saved water while maintaining the yield.

The RDI is an irrigation scheduling technique originally developed for pome and stone fruit orchards and was adopted successfully for wine grape production (McCarthy *et al.*, 2000). It provides means of reducing water use while minimizing adverse effects on yield (Pandey *et al.*, 2000). RDI is a controlled soil water deficit application during certain periods of a crop season (Kang *et al.*, 2000), or it is the one in which the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season (Kirda, 2000). English and Raja (1996) described three deficit irrigation case studies in which the reductions in irrigation costs were more than reductions in the revenue due to reduced yields.

Using RDI, substantial savings of water can be achieved with little impact on the quality and quantity of the crop yields. The objective of RDI is to save water by subjecting crops to periods of moisture stress by allowing different levels of management allowed depletion (MAD) having minimal effects on yields. To be successful, however, an intimate knowledge of crop behavior and monitoring of soil water in the root zone is required, as crop response to water stress varies considerably (Moutonnet, 2000).Neutron moisture probe has been widely used in agriculture, forestry, hydrology, and soil water engineering to monitor the changes in soil water content profiles (Marshall *et al.*, 1996). The use of neutron probe can help assess the water stress to plants and its availability in the root zone to schedule irrigations and amount of water to be applied.

Besides lab and field experiments, computer simulation models also offer an opportunity to simulate various management effects on soil water and crop yields. GLEAMS model is a point model and simulates management effects on soil water and chemical transport processes in and out of the root zone for various crops. This model has the hydrology, erosion, pesticide and nutrient components and has been widely used in the agriculture fields to simulate groundwater loading effects. This study aims at calibrating and validating the GLEAMS model for simulating management effects on maize to improve water use efficiency using deficit irrigation practices. Models, however, need to be calibrated using field/laboratory data before they can be used for solving practical problems. Therefore, this study has been designed to improve water use efficiency through deficit irrigation practices with the following specific objectives:

Monitor the soil water status in the root zone during maize growing season using neutron probe and measure crop yield response under various deficit irrigation treatments.

Calibrate and validate the GLEAMS model using field measured data on soil water and crop yields.

Simulate and identify the soil water deficit spans in relation to least sensitive vegetative growth stages during growing season to improve water use efficiency using deficit irrigation techniques.

## MATERIALS AND METHODS

The experiment was conducted, under field conditions, at the research area of the Department of Irrigation and Drainage, University of Agriculture, Faisalabad, during 2003, to study the effects of different water stress treatments on maize fodder production. The study area with latitude of 31$^{o}$24$^{'}$ N and longitude of 73$^{o}$05$^{'}$ E is situated on level plains, which has a mild slope from east to west with an average of about 0.2 – 0.3 m km$^{-1}$. The soils of the research area are of loam texture with organic matter contents ranging with depth from 0.62 to 0.26 %. Layout of various deficit irrigation treatments is shown in Figure 1.

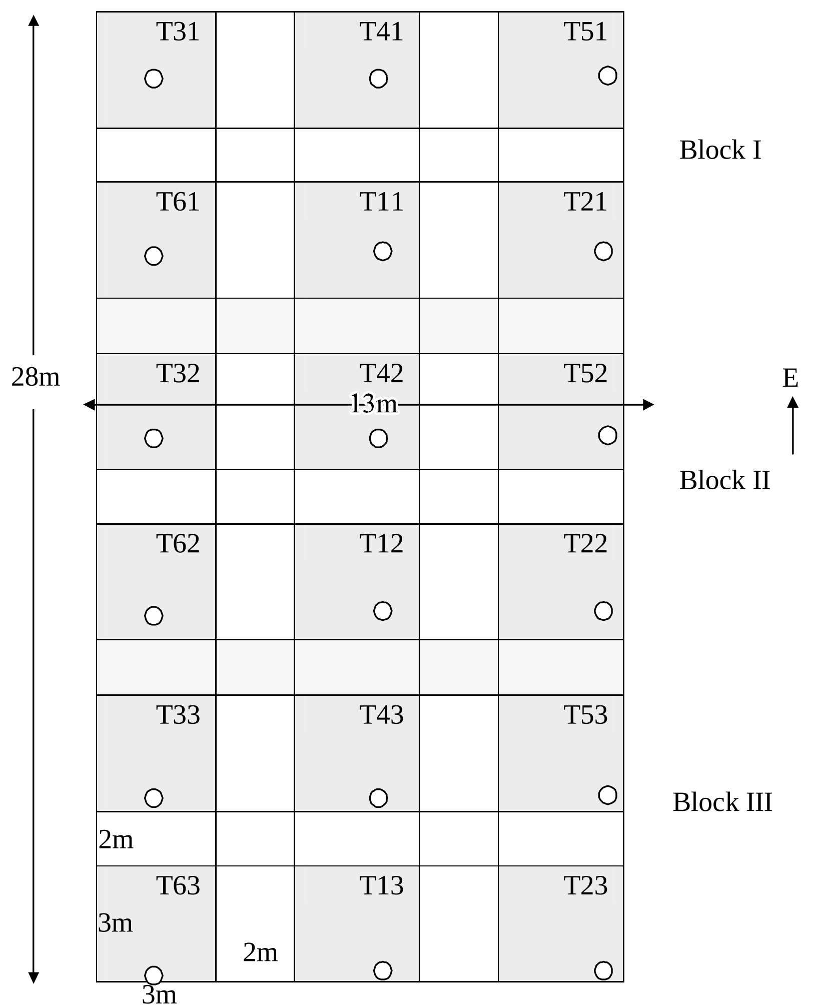


**Figure 1. Treatments layout under Randomized Complete Block Design (3 blocks) with plot size of 9 m2 (3 x 3 m) with two meters between the plots**

***Treatment description*:**

$T_1$ (control): Management allowed depletion, MAD = 30 %; 30 % depletion of total available water (TAW) throughout the growing season

$T_2$: MAD = 60 %; 60 %depletion of TAW throughout the growing season

$T_3$: MAD of 60 % only for 1st irrigation and MAD of 30% for the rest of irrigations

$T_4$: MAD of 60 % only for 2nd irrigation and remaining irrigations with MAD of 30 %

$T_5$: MAD of 60 % only for 3rd irrigation while the other irrigations with MAD of 30%

$T_6$: Alternate treatment; MAD of 60 % for one irrigation followed by MAD of 30 % for subsequent irrigation i.e. cyclic

The irrigation treatments were started after planting of maize (CV Golden) crop in the field. After sowing of maize on Oct 20, 2003, first irrigation of 70 mm was applied to all the experimental plots. Neutron probe was used to monitor the soil water depletion rates in the root zone and to schedule irrigations according to the specified MAD levels. The pumped groundwater was used for irrigation under different treatments. Pumped water was conveyed to different experimental units using a polyethylene pipe of 50mm dia.Soil properties are given in Table 1. The field was ploughed thoroughly on Oct. 14 using field tine cultivator and was planked for seedbed preparation. Experimental layout was prepared using 30 m tape and ridges were prepared manually using spade (Fig. 1). Maize crop was planted manually on Oct. 20 using seed drill keeping row to row spacing of 250 mm. Recommended level of N was used as urea at the rate of 250 kg $ha^{-1}$ and it was used in two splits (one on 20th Oct. and the other on 20th Nov.), both were applied at the vegetative growth stage of the crop. Crop was harvested after two months from planting to avoid the frost damage in the coming days. Soil water contents at field capacity and wilting point were determined using the pressure membrane apparatus. Evapotranspiration was determined by taking difference in the soil water content in the beginning and at the end of the period in between irrigations, taking into account the rainfall (if any) during the same period. Rainfall was divided into two parts, stored in the active root depth and percolated below that depth depending on the soil moisture status in the root zoon. Only the stored part was added to the calculated crop consumptive use.

Percolation was determined by taking difference in the soil water contents of the 600-800 mm soil layer. Any increase in soil water content of this layer was considered as percolation.

***Irrigation scheduling*:** The depletion of soil water in the upper 200mm of the soil was taken as irrigation criteria. When soil water reached at 22% level (MAD of 30%) or at 17 % level (MAD of 60%), irrigation water was applied. Irrigation depth was calculated for the upper 400mm root zone (Hussein, 2004).

***Water use efficiency (WUE)*:** Maize was harvested manually and fresh biomass yield was recorded using spring balance. WUE was calculated using the total water applied and biomass yield (eq.1).

$$WUE = \frac{Y}{TIW} \qquad (1)$$

Where

*WUE*: Water use efficiency, kg $ha^{-1}mm^{-1}$

*Y*: Biomassyield, kg $ha^{-1}$

*TIW*: Total irrigation water applied, mm

***GLEAMS model*:** GLEAMS model was calibrated using measured data of evapotranspiration (ET) for $T_6$ following the procedure given in the user manual (Knisel, 1999; Bakhsh and Kanwar, 2001). Adjustment of the most sensitive parameters in the hydrology component was made to get matching of the predicted and measured data on ET. The model was validated using measured data under treatments $T_1$, $T_2$, $T_3$, $T_4$ and $T_5$. *:* Several model performance indicators of percent difference, root mean square error, model efficiency, coefficient of residual mass were used to judge the model prediction capability. The validated model was used to compare different deficit irrigation scenarios.

***Management scenario simulations*:** Using validated GLEAMS model, the crop was auto-irrigated using GLEAMS. The simulated evapotranspiration (ET) was used to identify the best irrigation scheduling to improve water use efficiency through its use in calculating the predicted yields from different alternatives (Hussein, 2004). Statistical analysis of the fresh biomass yield and WUE data were

**Table 1. Soil physical properties of the soil of study area**

| Horizon | Depth (m) | Bulk Density ($Mg\ m^{-3}$) | Porosity | Field Capacity (%) | Wilting Point (%) | Soil Texture (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sand | Silt | Clay | Class |
| 1 | 0.2 | 1.40 | 0.47 | 27.4 | 10 | 44 | 35 | 21 | Loam |
| 2 | 0.4 | 1.44 | 0.46 | 27.1 | 10 | 45 | 35 | 20 | Loam |
| 3 | 0.6 | 1.52 | 0.43 | 26.5 | 10 | 43 | 34 | 23 | Loam |
| 4 | 0.8 | 1.54 | 0.42 | 26.1 | 10 | 43 | 34 | 23 | Loam |
| 5 | 1.0 | 1.57 | 0.41 | 26.0 | 10 | 43 | 34 | 23 | Loam |

*Note: Soil analysis was performed in the Soil Fertility Lab., Ayub Agricultural Research Institute (AARI), Faisalabad, Pakistan.*

carried out using MSTATC software. The comparisons among treatment means were made according to Duncan's New Multiple Range Test (Steel and Torrie, 1980).

## RESULTS AND DISCUSSION

***Soil properties*:** The soil was found to be loamy for the upper 1m depth with field capacity ranging from 27 to 26% for top to bottom horizons, wilting point of 10% and porosity varying from 47% for the top soil layers to 41% at 1m depth as shown in Table 1. With increase in depth from ground surface, bulk density increased from 1.4 to 1.57 $Mg/m^3$.

The chemical analysis of the soil is shown in Table 2, indicating no salinity problem, low organic matter contents and moderate in nutrients potential. Organic matter decreased with increase in depth. The top 200 mm soil depth was found to be having better nutrients status relatively which, however, decreased with depth.

***Irrigation scheduling*:** The soil water depletion rate from the soil depth of upper 200mm was used to determine the time of irrigations. Two values of soil water depletion or management allowed depletion (MAD) were set to start applying irrigation namely MAD of 30% and MAD of 60%. Irrigation schedules developed based on these criteria for different treatments are given in Table 3.Changes of soil water contents in the soil layer (0-200mm) are illustrated in Figures 2A (T1) to F (T6).

Under $T_1$ treatment, five irrigations were applied to maintain the 30% MAD level (Fig. 2, A (T1)). The slope of the depletion rate from field capacity to 30% MAD level gave the ET rate for each interval between the irrigations. The steeper the slope, the higher is the water depletion rate. This MAD level was monitored for soil depth of 200mm throughout the growing season. The maximum depletion rate was observed during first quarter at the rate of 2 mm $day^{-1}$. This fact can be attributed to high evaporation rate from the bare soil due to high temperatures (around 37°C) at the beginning of the growing season. The rainfall of 10 mm on Nov. 16 was utilized effectively for this treatment because the irrigation water applied earlier was depleted and soil moisture level was approaching to the threshold limit of MAD of 30% (Fig. 2, A (T1)). This rainfall was fully

**Table 2. Physical and chemical characteristics of the soil at the study area**

| Depth (m) | ECe ($dSm^{-1}$) | pH | Organic Matter (%) | Total N (%) | Available P ($mg\ kg^{-1}$) | Extractable K ($mg\ kg^{-1}$) | Textural Class |
|---|---|---|---|---|---|---|---|
| 0.00 – 0.20 | 0.25 | 7.6 | 0.62 | 0.112 | 5.0 | 135 | Loam |
| 0.20 – 0.40 | 0.23 | 7.6 | 0.36 | 0.074 | 6.0 | 75 | Loam |
| 0.40 – 0.60 | 0.31 | 7.6 | 0.31 | 0.069 | 5.5 | 60 | Loam |
| 0.60 – 0.80 | 0.31 | 7.6 | 0.26 | 0.065 | 4.2 | 60 | Loam |
| 0.80 – 1.00 | 0.25 | 7.7 | 0.26 | 0.065 | 4.0 | 48 | Loam |

*Note: Soil analysis was performed in the Soil Fertility Lab., Ayub Agricultural Research Institute (AARI), Faisalabad, Pakistan.*

**Table 3. Irrigation schedule and amount of water applied for different treatments**

| Treatments | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | | $T_2$ | | $T_3$ | | $T_4$ | | $T_5$ | | $T_6$ | |
| Date | Amount (mm) | Date | Amount (mm) | Date | Amount (mm) | Date | Amount (mm) | Date | Amount (mm) | Date | Amount (mm) |
| 20Oct. (293) | 70 | 20Oct. (293) | 70 | 20Oct. (293) | 70 | 20Oct. (293) | 70 | 20Oct. (293) | 70 | 20Oct. (293) | 70 |
| 27Oct. (300) | 11 | 15Nov. (319) | 23 | 15Nov. (319) | 23 | 27Oct. (300) | 11 | 27Oct. (300) | 11 | 15Nov. (319) | 23 |
| 10Nov. (314) | 11 | | | 29Nov. (333) | 16 | 6Dec. (340) | 31 | 10Nov. (314) | 11 | 29Nov. (333) | 16 |
| 28Nov. (332) | 15 | | | 11Dec. (345) | 21 | | | 9Dec. (343) | 33 | | |
| 8Dec. (342) | 17 | | | | | | | | | | |
| **Total** | **124** | | **93** | | **130** | | **112** | | **125** | | **109** |

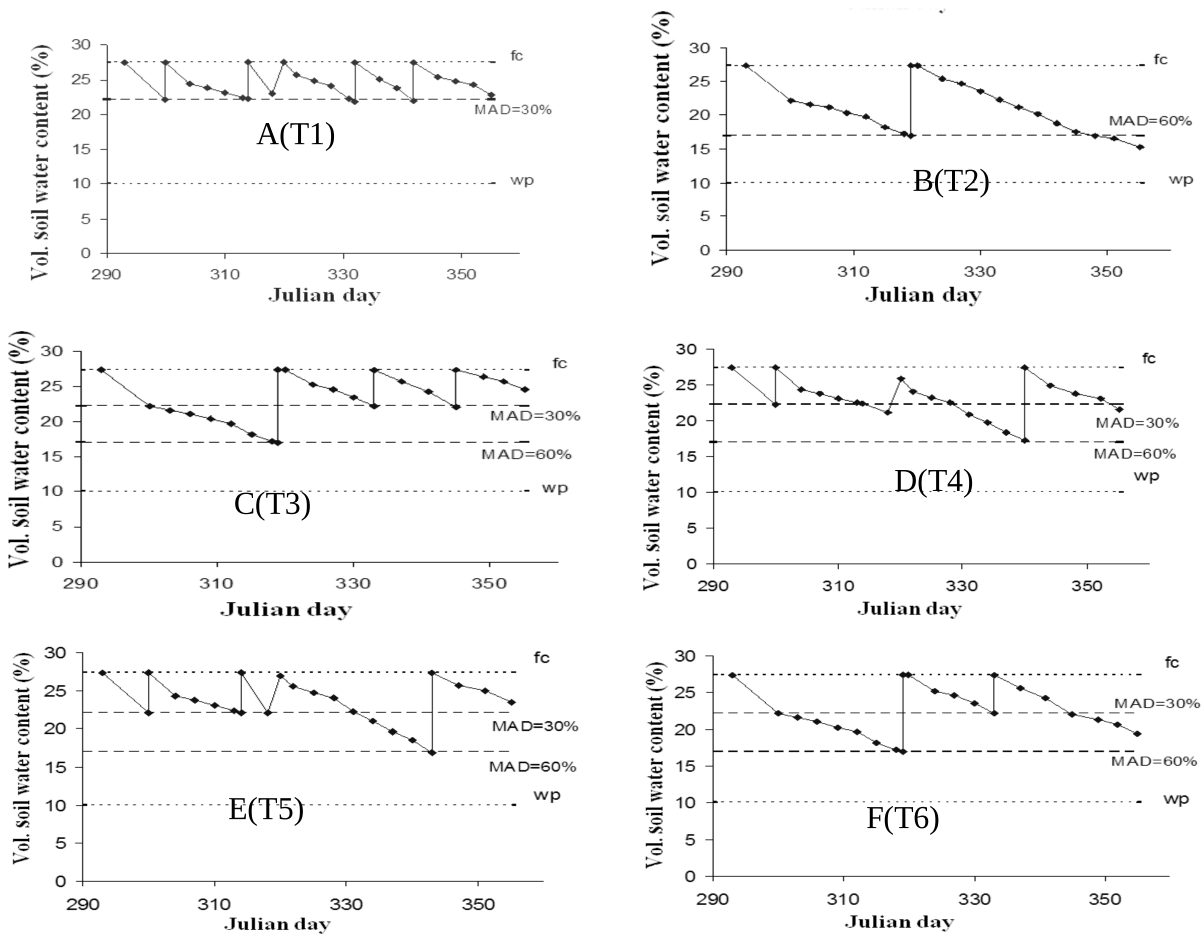


**Figure 2. Soil water content changes with time in the upper 200 mm during the growing season for treatments from A(T1) to F(T6).**

utilized because 11 mm water was required to bring the soil moisture from depleted level of 30% MAD to the field capacity level and rainfall of 10 mm was adequate at that time.

Under $T_2$ treatment, two irrigations were applied to maintain the 60% MAD level throughout the growing season (Fig. 2,B(T2)). The second irrigation on Nov. 15 was followed by a 10 mm of rainfall on Nov. 16. No change in soil moisture content was observed as it was already at the field capacity level after receiving 2nd irrigation. Presumably the rainfall of 10 mm moved beyond the active root depth of 0-600 mm**.** In this case, the rainfall did not contribute in changing the soil moisture content profile (Fig. 2, B (T2)) because irrigation of 23 mm was applied just 1 day prior to the rainfall so for treatment T2, rainfall was lost as deep percolation losses. Under $T_3$ treatment, four irrigations were applied. Second irrigation was applied when soil water content reached the 60% MAD level. The subsequent irrigations were applied to maintain the 30% MAD level for rest of the growing season (Fig. 2, C (T3)). In this case, the rainfall was not used effectively as the soil moisture was already at the field capacity level after receiving 2nd irrigation of 23 mm just one day prior to the rainfall of 10 mm. The maize crop used less water from the last irrigation (21 mm on 11 Dec.) because it was harvested on 22 Dec. and a significant part of it (about 10 mm) was stored in the root zone.

Under $T_4$ treatment, three irrigations were applied to maintain the 30% MAD level except for the 3rd irrigation where MAD was allowed to reach 60% (Fig. 2, D (T4)). Due to good distribution of irrigations and rainfall for this treatment, the crop used all the applied water, as well as 10 mm of rainfall. Rainfall was used effectively as the soil moisture content was closer to 30% MAD level prior to the rainfall and the effect of rainfall on raising the soil moisture level is apparent from Figure 2, D(T4).

Under $T_5$ treatment, four irrigations were applied. The changes in the soil water content in the upper 200 mm of soil were similar to those of $T_4$, except for the last irrigation of 33 mm, where about half of it was stored in the root zone after harvesting (Fig. 2, E(T5)). The rainfall of 10 mm contributed in raising the soil moisture contents from 30% MAD level to closer to the field capacity level as happened to the soil moisture contents for treatments of T1 and T4.Under $T_6$, three irrigations were applied. Soil water depletion was allowed to reach 60% MAD level for the second irrigation, then to 30% MAD level for the third irrigation (Fig. 2, F(T6)). In this case for treatment T6, rainfall was not used effectively and was lost as deep percolation. The maximum amount of water applied was under $T_3$ (130 mm) and the minimum was 93 mm under $T_2$ with 60% MAD level (Table 3).

***Soil water extraction pattern*:** The graphical presentation of the soil moisture extraction by plant roots under different treatments is shown in Fig. 3 A(T1) to F(T6) and these figures show a clear picture of the root growth rate with development of the crop growth stages. These figures also show that the crop m*et al*most all of its water needs from top 400 mm of the soil depth up to the end of November. The depletion zone continued to grow deeper but with a different pattern depending on the soil water stress level. Application of more frequent irrigations for $T_1$ to keep the soil water stress level within the desired limits of lower tension resulted in a shallower depletion zones (top 400 mm of the soil depth) (Fig.3, A(T1)), whereas in the other treatments the case is different (Fig. 3, B(T2) to F(T6)). Under $T_1$,the soil water availability required more frequent irrigations, and the plants presumably met a major portion of the evapotranspiration demand by extracting water from the upper 400 mm of soil depth, which restricted root growth and resulted in a shallower depletion zone. Chaudhry (1985) and Haiso (1973) suggested that when water supply was abundant in the upper soil layers, roots did not absorb water from the deeper soil layers. In a higher soil water stress regimes ($T_2$ and $T_6$), roots grew more rapidly towards a deeper layer of soil when water was readily available there (Fig. 3, A(T2) to F(T6)) (Chaudhry and Bhatnagar, 1980; Pandey*et al.*, 2000).Water stress imposed during early stage of growing season ($T_3$) enhanced root growth rate (Fig. 3, C(T3)), whereas less root growth rate was observed under water stress coming later in the growing season of $T_4$ and $T_5$ treatments (Fig. 3, D(T4) and E(T5)). The soil water extraction pattern shows the root development zone. Differences in soil water extraction pattern stem from the fact that roots follow soil water status. It is clear from Fig. 3 A(T1) to F(T6) that the crop met most of its water requirements during first month of its growing season from the soil depth oftop 200 mm. Then due to differences in soil water status under different treatments, crop roots reacted differently. The maximum water depletion for 400 to 600 mm soil layer was observed under $T_2$ (9%) (Fig. 3, B(T2)), while the minimum was observed under $T_1$ (2.4%) (Fig.3, A(T1)).The soil water extraction pattern at a higher water stress level indicated deepening of crop roots whereas at a low water stress level, root development was restricted.

***Effect of water stress timing on the biomass yield*:** The data regarding biomass above the ground are given in Table 4. It is clear that water stress timing had a statistically significant ($p \leq 0.05$) effect on fresh weights of maize fodder yield. The highest average value was observed for $T_1$ with 8933 kg ha$^{-1}$, whereas the lowest average fodder yield was observed for $T_2$ with 7994 kg ha$^{-1}$, significantly different from those of T1 and T5. Treatment mean of T1 was different from all but not from those of T3 and T5 showing that stress at 2$^{nd}$ and 4$^{th}$ irrigations was least sensitive to maize fodder yield. The results presented by Stegman (1986) and Pandey *et al.* (2000) showed similar trend. Also Khan *et al.* (2001) reported that water stress decreased fodder and grain yields.

***Effect of water stress timing on water use efficiency*:** The data pertaining to water use efficiency, listed in Table 5, reflect that water stress timing had a statistically significant effect on water use efficiency. The maximum mean value of 86 kg ha$^{-1}$mm$^{-1}$ was calculated for $T_2$ and the lowest value of WUE for $T_3$ was 64.30 kg ha$^{-1}$mm$^{-1}$. Kirda (2000) reported that under deficit irrigation practices, the relative yield decrease was proportionately lesser than the decrease in application of irrigation water. Therefore, one should expect crop WUE to increase even if crop yields decrease. The results of $T_2$, $T_4$, and $T_6$ treatments are in close agreement with those of Kirda (2000). This was not the case with $T_3$ and insignificantly with $T_5$. In $T_3$ and $T_5$ the crop did not use the last irrigation fully (21 mm for $T_3$ and 33 mm for $T_5$) and adequate part of it was stored in the soil after harvesting the crop (10mm for $T_3$ and 15 mm for $T_5$).The analysis of variance (ANOVA) revealed that treatment effects on WUE were significant at 5% probability level. After this significant treatment effect, DMR test was conducted to compare difference among the treatment means (Table 5).

***Model calibration*:** The simulations of irrigations applied to treatment $T_6$ resulted in water balance components in the hydrology output file. These results were compared with the observed data. It shows that there is close agreement between calculated ET and predicted ET and % difference and CRM values were within acceptable limits (Table 6) between the predicted and calculated data. The soil water contents, however, were under predicted all over the growing season. The predicted runoff was equal to zero and no runoff was observed in the field since the plots were constructed to prevent surface runoff. Only for treatments T2, T3, and T6 there was a percolation of 7 mm to the 600-800mm soil layer. Model simulations of percolation matched with the observed data as percent difference was less than 5% (Table 7). Overall, GLEAMS model accurately predicted the observed data on ET, runoff, and percolation while simulations of the soil water contents were under-estimated (Hussein, 2004).

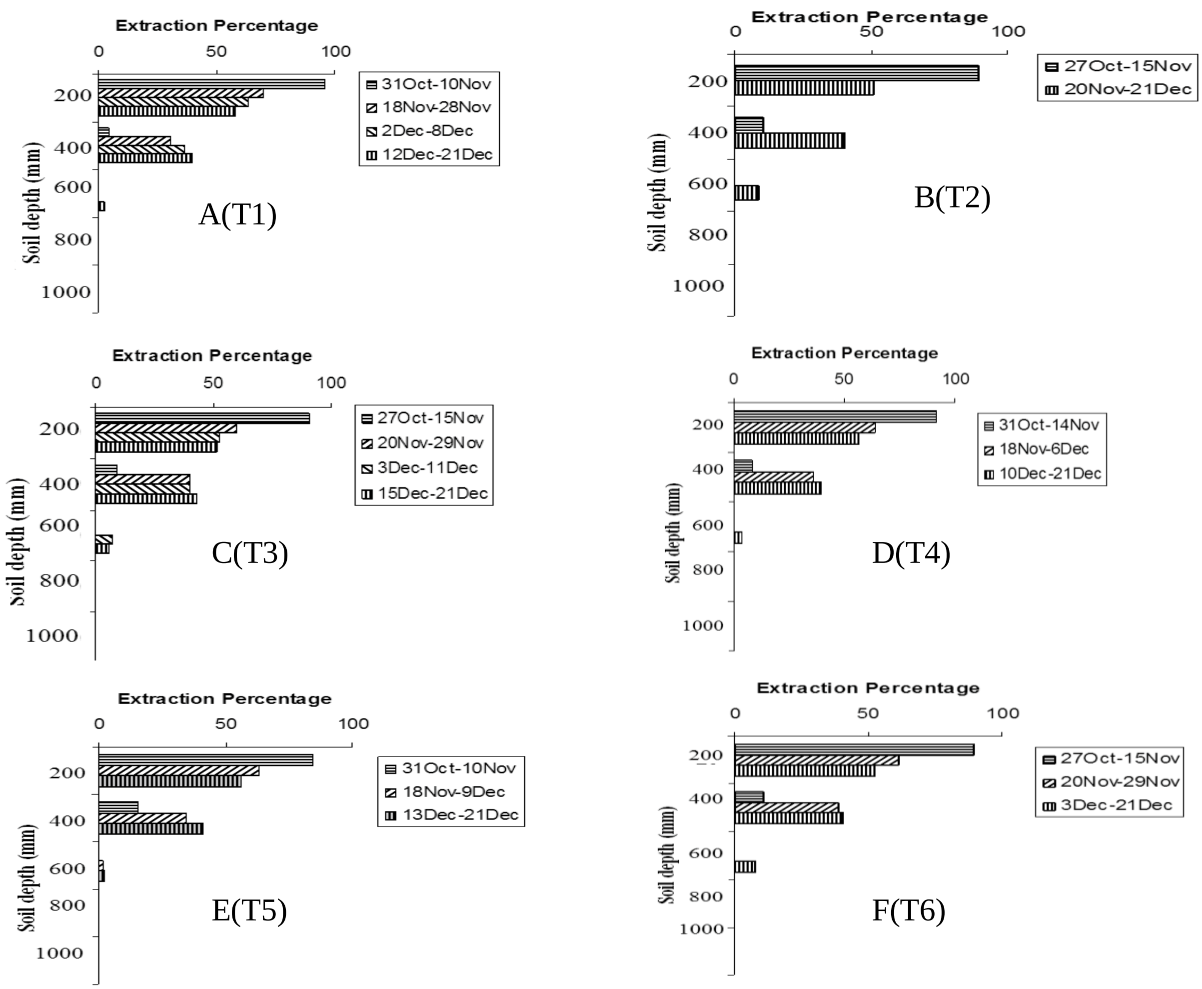


**Figure 3. Soil water extraction pattern monitored during growing season for treatments from A(T1) to F(T6).**

**Table 4. Biomass yield of different treatments in Kg ha$^{-1}$**

| Treatments | Replications | | | Total | Mean | Yield reduction Kg ha$^{-1}$ | Yield reduction % |
|---|---|---|---|---|---|---|---|
| | $R_1$ | $R_2$ | $R_3$ | | | | |
| $T_1$ | 9200 | 8819 | 8780 | 26799 | $8933_a$ | 0.0 | 0.0 |
| $T_2$ | 7862 | 7929 | 8190 | 23981 | $7994_c$ | 939 | 10.5 |
| $T_3$ | 8341 | 8758 | 7972 | 25071 | $8357_{abc}$ | 576 | 6.4 |
| $T_4$ | 8753 | 7791 | 8257 | 24801 | $8267_{bc}$ | 666 | 7.5 |
| $T_5$ | 8659 | 9232 | 8663 | 26555 | $8852_{ab}$ | 81 | 0.9 |
| $T_6$ | 8421 | 8042 | 7618 | 24081 | $8027_c$ | 906 | 10.1 |

**Table 5. Water use efficiency of different treatments in kg ha$^{-1}$ mm$^{-1}$**

| Treatments | Replications | | | Total | Mean |
|---|---|---|---|---|---|
| | $R_1$ | $R_2$ | $R_3$ | | |
| $T_1$ | 74.2 | 71.1 | 70.8 | 216.1 | $72.0_b$ |
| $T_2$ | 84.5 | 85.3 | 88.1 | 257.9 | $86.0_a$ |
| $T_3$ | 64.2 | 67.4 | 61.3 | 192.9 | $64.3_c$ |
| $T_4$ | 78.2 | 69.6 | 73.7 | 221.5 | $73.8_b$ |
| $T_5$ | 69.3 | 73.9 | 69.3 | 212.5 | $70.8_b$ |
| $T_6$ | 77.3 | 73.8 | 69.9 | 221.0 | $73.7_b$ |

**Table 6. Percentage difference (%D) and coefficient of residual mass(CRM) for ET of different treatments**

| | Treatments | | | | | |
|---|---|---|---|---|---|---|
| | **T1** | **T2** | **T3** | **T4** | **T5** | **T6** |
| **Calculated ET (mm)** | 79.0 | 72.0 | 73.6 | 73.4 | 78.4 | 72.0 |
| **Predicted ET (mm)** | 73.8 | 66.1 | 73.9 | 73.8 | 73.7 | 73.5 |
| **%D** | -6.58 | -8.19 | 0.41 | 0.54 | -5.99 | 2.08 |
| **CRM** | -0.07 | -0.08 | 0.00 | 0.01 | -0.06 | 0.02 |

**Table 7. Percentage of difference (%D) for percolation from different treatments**

| | Treatments | | | | | |
|---|---|---|---|---|---|---|
| | **T1** | **T2** | **T3** | **T4** | **T5** | **T6** |
| **Observed percolation (mm)** | 0.0 | 7.0 | 7.0 | 00 | 00 | 7.0 |
| **Predicted percolation (mm)** | 6.0 | 7.3 | 7.3 | 00 | 6.0 | 7.3 |
| **% Difference** | - | 4.29 | 4.29 | - | - | 4.29 |

***Model validation*:** Model performance was tested by comparing measured data on evapotranspiration (ET), deep percolation, runoff, and soil water contents with the predicted data. For runoff component, the predicted runoff was zero, and in the field no runoff was observed. For treatments $T_2$, $T_3$, and $T_6$ there was an observed percolation of 7 mm while the model predicted percolation was 7.3 mm and % difference was 4.29 (7.3 mm vs. 7 mm) (Table 7). For other three treatments with no observed percolation, the predicted percolation for $T_4$ was zero and the model predicted percolation of 6 mm for $T_1$ and $T_5$. In fact, GLEAMS model has assumption that when soil moisture was more than that at the field capacity level, rapid percolation was always possible so that daily soil moisture content never exceeded the field capacity level. Rekolainen *et al*. (2000) reported that GLEAMS, being a capacity type model, simulates changes in soil moisture which appear to be rapid compared with the observed values. During wet season, or after rainfall events, GLEAMS sets soil moisture to the selected field capacity level. For ET, goodness of fit was indicated using temporal evaluation method by plotting calculated and predicted daily ET data during the growing season (Figs. are not shown here).

Also other model performance indicators, such as percentage of difference %D, coefficient of residual mass CRM, root mean square error RMSE, and model efficiency EF, were used to judge the model prediction capability. Percentage of difference with negative sign indicated under-predicting pattern in the simulations (Table 8)**.** In general, GLEAMS slightly under-predicted ET data. Similarly, model evaluation based on various indicators of RMSE (=5.55%), and EF (=-0.71), were found to be satisfactory (Table 9). Hedden (1986) described RMSE criteria for deciding goodness of fit for models such as GLEAMS. As model was parameterized using available site specific data,the overall RMSE was 5.55 % which indicated the reliable prediction capability of the GLEAMS model for ET.The overall difference between calculated and predicted ET, when averaged for validation treatments, was -4 % (72 mm vs. 75 mm) as shown in Table 9.

GLEAMS significantly under-predicted soil water contents for different treatments during growing season (for example, 22 vs. 55 mm for the upper 200mm at field capacity level). Overall, simulated soil water storage agreed with the measured data trend. Similar results of model predictions of soil water content have been reported by Rekolainen *et al*. (2000). They concluded that the model performance against the observed data was relatively better during dry season but during wet season, the model had difficulties to match the higher observed values in deeper soil layers. In general, differences between observed and simulated results stem from the fact that GLEAMS was designed to compare and evaluate the relative effects of management practices and not the absolute data.

***Simulated ET for proposed irrigation management scenarios*:** After calibrating and testing the model, different deficit irrigation simulations were carried out. Overall, confidence in the ability of GLEAMS model to realistically represent the management scenarios was high because of the satisfactory simulation of the water balance components and close agreement between simulated and measured data. The scenario simulations were aimed at increasing water use efficiency, WUE.GLEAMS auto irrigation option was used; irrigation was automatically applied by the model when soil water content reached a predetermined level of plant available water (lower limit; S1=25%, S2=30%, S3=40%, S4=50%, and S5=60% of available water), applying sufficient water to increase the soil water to a selected level of plant available water content (upper limit; 90%).

The GLEAMS predicted irrigation water for different scenarios (Table 10). The actual yield expected from such irrigation water was calculated (Hussein, 2004).As a result the calculated yield for different scenarios is shown in Table 10. Therefore, different scenarios resulted in a percentage reduction in yield varying from 5 to 23% compared with maximum yield. To select the best scenario for achieving the

**Table 8. Measured evapotranspiration data for different treatments**

| Treatments | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | | $T_2$ | | $T_3$ | | $T_4$ | | $T_5$ | | $T_6$ | |
| **Date** | **ET (mm)** | **Date** | **ET (mm)** | **Date** | **ET (mm)** | **Date** | **ET (mm)** | **Date** | **ET (mm)** | **Date** | **ET (mm)** |
| 20Oct-27Oct | 11 | 20Oct-15Nov | 23 | 20Oct-15Nov | 23 | 20Oct-27Oct | 11 | 20Oct-27Oct | 11 | 20Oct-15Nov | 23 |
| 27Oct-10Nov | 11 | 15Nov-21Dec | 49 | 15Nov-29Nov | 19 | 27Oct-6Dec | 41 | 27Oct-10Nov | 11 | 15Nov-29Nov | 19 |
| 10Nov-28Nov | 25 | | | 29Nov-11Dec | 21 | 6Dec-21Dec | 21 | 10Nov-9Dec | 43 | 29Nov-21Dec | 30 |
| 28Nov-8Dec | 17 | | | 11Dec-21Dec | 11 | | | 9Dec-21Dec | 13 | | |
| 8Dec-21Dec | 15 | | | | | | | | | | |
| **Total** | **79** | | **72** | | **74** | | **73** | | **78** | | **72** |

**Table 9. GLEAMS model predicted ET for different treatments with various model performance indicators**

| Variables | Treatments | | | | | | For validation treatments (T1-T5) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **T1** | **T2** | **T3** | **T4** | **T5** | **T6** | **Mean** | **RMSE (%)** | **EF** |
| **Calculated ET (mm)** | 79.0 | 72.0 | 73.6 | 73.4 | 78.4 | 72.0 | 75.0 | 5.55 | -0.71 |
| **Predicted ET (mm)** | 73.8 | 66.1 | 73.9 | 73.8 | 73.7 | 73.5 | 72.0 | | |

**Table 10. Water use efficiency for different scenarios.**

| | Scenarios* | | | | |
|---|---|---|---|---|---|
| | **S1** | **S2** | **S3** | **S4** | **S5** |
| **Predicted irrigation (mm)** | 110 | 108 | 125 | 133 | 128 |
| **Yield (kg ha$^{-1}$)** | 7672 | 7492 | 9023 | 9743 | 9293 |
| **Yield reduction (%)** | 21.3 | 23.1 | 7.4 | - | 4.6 |
| **WUE (kg ha$^{-1}$ mm$^{-1}$)** | 69.7 | 69.4 | 72.2 | 73.3 | 72.6 |

* S1:25-90%; S2:30-90%; S3: 40-90%; S4: 50-90%; and S5: 60-90% of available water.

best water use efficiency, model predicted irrigations for each scenario were considered.

The scenario, S4, gave the highest water use efficiency of 73.3 kg ha$^{-1}$ mm$^{-1}$. S1 scenario gave a WUE of 69.7kg ha$^{-1}$ mm$^{-1}$ with 21% reduction in yield and a minimum WUE. According to these results, the fourth scenario (S4; 50 to 90% of available water) was recommended. Also S3 and S5 can be good alternatives. In general, RDI has the potential of saving water with minor effects on yield (Kirda, 2000, Moutonnet, 2000).

***Conclusions*:** Based on field experimental data and GLEAMS model simulations analysis, treatment effects were found to be significant at 5% significance level. The treatment with 30% MAD level had significantly more yield than those of all other treatments while T2 had the maximum WUE because of higher water stress level of 60% MAD and having less application of irrigation water. The relative effects of management scenario simulations using validated GLEAMS model showed that option of keeping soil moisture within the range of 30 to 90% of available water had better WUE. From simulated scenarios, the S4 option of keeping soil moisture within 50 to 90% of available water gave the highest water use efficiency of 73.3 kg ha$^{-1}$ mm$^{-1}$. These results indicate that the regulated deficit irrigation technique is useful and has the potential to increase water use efficiency as demand for water increases day by day. Such studies need to be conducted for all major crops. The modeling approach can be helpful to assess the impacts of different deficit irrigation alternatives on the crop growth.

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