# Irrigation Scheduling Scenarios Studies for a Maize Crop in Tanzania Using a Computer-based Simulation Model

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## ABSTRACT

Irrigation scheduling is viable practice that can enhance crop production and greater profit for farmers. It can lead to significant water saving, reduced environmental impact of irrigation and improved sustainability of irrigated agriculture. In order to define appropriate irrigation scheduling protocols for optimal water management and crop response and make recommendation to farmers, there is a need for proper evaluation of feasible irrigation scheduling options. This paper presents scenarios studies of different irrigation scheduling options for a maize crop in Mkoji sub-catchment of the Great Ruaha River Basin in Tanzania using a computer-based simulation model. The model called ISIAMod was used to simulate crop, soil water balance and crop water productivity responses for different intervals of irrigation (7, 9, 10, 12, and 14 days) and water application depths (WAD) ranging from 30 to 70 mm per irrigation. The model simulated outputs for the different irrigation intervals were compared using the 7-day irrigation interval as a reference, being the conventional scheduling practice for maize crop in the study area. The comparison was based on percent losses or gains in the grain yields; seasonal water applied; seasonal evapotranspiration, and deep percolation. The results showed that although irrigating at intervals longer than the conventional 7 days, whether throughout the crop growing season or at some growth stages of the crop, led to significant reduction in grain yield, there was also a significant reduction in seasonal water applied in the field and the associated deep percolation losses. The crop water productivity (in terms of water applied) for the 7-day scheduling interval was higher than the other scheduling intervals only when WAD per irrigation was less than 45 mm. When WAD per irrigation exceeded 45 mm, the crop water productivity of the 7-day irrigation interval fell below those of the 9-, 10-, and 12-day intervals by between 5 and 20 %. The optimal irrigation scheduling scenario which maximize grain yield and minimized deep percolation losses in the study area was the 9-day irrigation interval at 50 mm a 10-day irrigation interval at WAD of 55 mm. Yield losses associated with these two scheduling options when compared with the 7-day irrigation interval were only 17 and 22 % for the 9 and 10-day frequencies, respectively. But the reduction in deep percolation was about 50 and 58 % for the 9- and 10-day irrigation interval, respectively. The irrigation scheduling scenarios showed a technical feasibility of reducing the water supply for irrigation and an appealing tradeoff between yield reductions and water saved. However, whether irrigation farmers who are always profit-oriented are ready to compromise such tradeoff will remain a subject of interest both farmers and water managers..

**Keywords**: Crop water productivity, crop yield, irrigation scheduling, simulation model.

## 1. INTRODUCTION

A key practice in irrigation water management that can facilitate the achievement of the goal of producing more crop per drop of water, a slogan of Food and Agricultural Organization (FAO, 2003) and International Water Management Institute (Molden *et al.*, 2003), is irrigation scheduling. Irrigation scheduling is the technique to timely and accurately give water to crop. Jensen (1981) referred to irrigation scheduling as “a planning and decision-making activity that the farm manager or operator of an irrigated farm is involved in before and during most of the growing season for each crop that is grown”. Irrigation scheduling has been described as the primary tool to improve water use efficiency, increase crop yields, greater availability of water resources, and provoke a positive effect on the quality of soil and groundwater (FAO, 1996). As the water resources of many river basins dwindles and the competition for water in the river basins increases, irrigated agriculture which is the largest water user in many river basins need to continue to search for feasible irrigation scheduling strategies other than those currently in practice, which can be adopted to cope with this rising challenges.

Irrigated agriculture is growing rapidly in Tanzania. One of the many places in the country where irrigated agriculture is having a strong positive impact in the livelihood of the people is the Mkoji sub-catchment of the Great Ruaha River Basin (SWMRG-FAO, 2003; Kadigi *et al.*, 2004). Paddy rice is grown under rain-fed supplemented with irrigation while in the dry season maize, beans, vegetables, and fruits are cultivated under total irrigation in the sub-catchment. In Mkoji sub-catchment, irrigation scheduling is not an entirely new subject to farmers. During the dry season, irrigation farmers in many of the irrigation schemes practice rotational water abstraction as a measure to minimize conflict over water. Farmers are only allowed to open their water intake and abstract water from the streams on their scheduled date. This practice automatically constrains the farmers to irrigate their crops at fixed interval of irrigation throughout the crop growing season. In one of the irrigation schemes in Mkoji sub-catchment, the *Igurusi ya Zamani* Traditional Irrigation Scheme (IZTIS) for example, the scheduled interval of rotational water abstraction is seven days. So farmers can only irrigate their maize, beans, and tomato once a week. Such method of rotational water-delivery to farmers and the resultant fixed irrigation scheduling is commonly practiced in some countries of Asia and Africa. It is popularly referred to as ‘warabandi’ among Indians/Pakistanis (Bandaragoda, 1998, Qureshi *et al.*, 2002). The usual practice in many of the irrigation schemes is to fix the water rotation on 7 to 10 days interval (Bandaragoda, 1998; Joshi, 2001, Qureshi *et al.*, 2002). Although there might not be any scientific basis for such interval, and on the contrary, such interval might not be the optimum for some crops and some crop growth stages; a fixed irrigation interval of 7 or 10 days is easier for farmers to keep track of their next irrigation days.

As the water resources of the Mkoji sub-catchment continues to be stressed due to rapid increase in dry season irrigation activities, over-abstraction of water from the streams (Rajabu *et al.*, 2005), and the agitation for more access to water by non-agricultural water users in the area, one option that ready comes to the mind is for irrigation farmers (who uses more water) to practice deficit irrigation scheduling. Since the rotational water delivery method is well entrenched and acceptable among the irrigation farmers in the area, two feasible approaches of imposing deficit irrigation are by increasing the intervals of irrigation, and by reducing or maintaining the interval of irrigation but reducing the water application depth (WAD). In an irrigation scheme where competition for and conflict over water is high, reducing the interval of irrigation and trying to reduce WAD will mean more frequent irrigation, and that could increase the agitation for irrigation opportunity among farmers. It is also practically difficult to get peasant irrigation farmers to apply water less than what they think or know is required by their crop. Based on these constraints the approach of imposing deficit by increasing the interval of irrigation seems more practicable. However the impact of such increase in irrigation interval on crop growth and yield, soil water balance and water productivity needs to be well understood.

In order to recommend appropriate deficit irrigation scheduling protocols for optimal water management to farmers, there is a need for a comprehensive evaluation of different irrigation scheduling options. The outcome of such evaluations will constitute a body of knowledge which can be used to advise farm. Evaluation of irrigation scheduling strategies may be carried out directly by conducting field trials. However, field experiments have two serious setbacks. According to Drooger *et al.* (2000) field experiments are expensive and time consuming, and are subject to uncontrolled condition such as weather, diseases, etc. Secondly, it is practically difficult to analyze long-term effect and large impact scenarios on the field. One cheap and efficient way to conduct an evaluation of the impacts of irrigation scheduling practice is to use computer-based simulation models. One interesting aspect of computer models is that they allow for the selection and evaluation of several alternative strategies (Campos *et al*., 2003). Cabelguenne *et al.* (1995) and Rinaldi (2001) have used EPIC model to evaluate different irrigation scheduling strategies for maize in southwestern France and soybean in southern Italy, respectively. Rodrigues *et al.* (2001) used ISAREG model to simulate deficit irrigation as a coping strategies for cereal and horticultural crops in Tunisia, while El Amani *et al*. (2001) conducted an economic analysis of the impact of deficit irrigation scheduling for cereals and horticultural crop based on the simulated results using ISAREG model.

This paper presents the use of a computer-based crop growth cum irrigation scheduling model named **I**rrigation **S**cheduling **I**mpact **A**ssessment **M**odel (ISIAMod) to study the impact of different irrigation scheduling scenarios for a maize crop in Mkoji sub-catchment in Tanzania. The aim was to obtain insight as to what are the possible impacts on crop yield, seasonal water applied, crop evapotranspiration and deep percolation losses if the interval of water rotation and by extension the irrigation interval for the maize crop is increased beyond the conventional seven days practiced in the area. Such insight would be useful when making recommendation on appropriate irrigation scheduling protocols for optimal water management to farmers.

## 2. MATERIALS AND METHODS

### 2.1 Study Location

The Mkoji sub-catchment (MSC) lies between latitudes $7^0$48’ and $9^0$25’ South, and longitudes $33^0$40’ and $34^0$09’ East (SWMRG, 2003). It is a sub-catchment of the Great Ruaha River Basin, which is one of the four sub-basins of the Rufiji River Basin in Tanzania. The MSC covers an area of about 3400 km$^2$. The mean annual rainfall in the study location is about 800 mm. The rains fall between November and April. The study area has a unimodal type of

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rainfall. Mean daily maximum temperatures range from 28°C to 32°C, while minimum temperature ranged from 9.5°C to 19.5°C, respectively. The highest values are recorded in October and November while the lowest values are experienced in June and July. The mean daily net solar radiation varies from 7.5 MJ/$m^2$/day to 12.3 MJ/$m^2$/day. The average annual open pan evaporation is about 2430 mm, and the total open pan evaporation from June to October when dry season farming takes place is about 1080 mm.

## 2.2 The Computer Simulation Model Used for the Study

The **I**rrigation **S**cheduling **I**mpact **A**ssessment **M**odel (ISIAMod) was created by Igbadun (2006) for simulating crop growth processes, soil water balance of a cropped field, and water management response indices (WMRI). The indices are used to explain the impact of an irrigation scheduling decision. ISIAMod is a process-based model. It runs on daily time-step, from crop planting date to crop physiological maturity date. The input data required in the model are classified into climate soil, crop, rainfall, and irrigation scheduling decisions. The minimum weather data required are daily maximum and minimum ambient temperatures for the duration of crop growth. Other weather parameters which are optional include daily records of wind speed, maximum and minimum relative humidity, sunshine hour or solar radiation. ISIAMod uses the weather data to compute daily reference evapotranspiration (ETo) based on the FAO-Penman-Monteith (FPM) or the Hargreaves methods as described in Allen *et al*. (1998).

The soil input data include volumetric soil moisture content at field capacity and at wilting point, initial soil moisture contents, bulk density, and the percentage of sand in the soil texture. The soil profile is to be divided into a minimum of four and a maximum of ten layers, and each layer is divided into a number of compartments. The total number of compartment the entire soil profile can be divided is sixty. The discretization of the soil profile into layers and compartments is to facilitate numerical computation of the soil water flux. The soil input data listed above are required for each soil profile layer. The numbers of soil layers and compartments per layer to be considered in a simulation are to be specified by the user as part of the soil input data. The depth of each layer is also to be specified. However, the depth of the topmost profile layer is restricted to 20 cm thick, and the layer can only be divided into two compartments. The top of the two compartments of the first layer constitutes the evaporation zone. Transpiration is assumed negligible in the top compartment.

The infiltration and distribution of water within the soil profile is based on the “tipping bucket” method (Campbell and Daiz, 1988; Zhang *et al.*, 2004). The active root zone starts from the second compartment of the first layer. Each compartment is assumed to be filled with water to field capacity after irrigation or heavy rainfall, and then passes on any remaining water to the compartment below. Any water which passes beyond the bottom layer of the profile depth is assumed lost to deep percolation. No upward movement of water in the profile is allowed. ISIAMod assumes irrigation and rainfall as the only sources of water input to the cropped field. Through the process of evaporation, water is removed from the uppermost soil layer of the cropped field. Through the process of transpiration water is removed from the crop root zone depth which increases down the soil profile as the crop rooting depth. Soil water is assumed held in an unsaturated state within the crop root zone for crop use. Soil moisture beyond the potential at which water can be held in the plant root zone is drained out of the zone via the process of deep percolation. The model assumes a one-dimension vertical movement of water in the soil profile. It assumes that the soil has a high hydraulic conductivity, with no drainage impediment. Therefore, there is no temporary storage of water in excess of field capacity beyond two days. It also assumes a soil with a deep water table, and consequently no significant contribution from groundwater to the plant root zone.

The crop input data include maximum rooting depth, maximum leaf area index, potential (non-water limited) harvest index, radiation use efficiency (RUE), radiation extinction coefficient, and peak crop water use coefficient ($k_c$). Others include crop base and optimum temperatures; leaf area index shape factors; water-limited harvest index adjustment factors; crop planting, emergence, and physiological maturity dates; days from planting for the start of each of the four crop growth stages, and fraction of the crop growth duration at which leaf area index started to decline. The model divides the crop growth stages into four: crop establishment, vegetative, flowering and maturity (which include seed formation through to maturity). The method of simulating biomass production in ISIAMod is similar to EPIC model (William *et al*., 1989)

The irrigation scheduling input data include the time of irrigation and water application depth per irrigation. ISIAMod was designed to give the user five options of irrigation timing criteria and three options of water application depth (WAD) from which the user can select. The five options of irrigation timing criteria include: (1) User's specified dates of irrigation and depths of water to be applied; (2) Fixed irrigation interval throughout the crop growing season; (3) Fixed irrigation interval per growth stage. This allows the user to adopt different irrigation interval for the different growth stages of the crop; (4) Fixed maximum allowable depletion (MAD) through out the crop growing season; (5) Fixed MAD per growth stage. This permits the user to adopt different MAD for the different growth stages of the crop.

The three options of water application depth include: (1) Depth of water equals the amount of water used by the crop at user's defined water application efficiency; (2) Fixed depth of water throughout the crop growing season; (3) Fixed water application depth per growth stage. This option allows the user to apply different WAD for the different growth stages. ISIAMod allows a combination of any of the timing criteria with any water application depth options. However, this rule does not apply when the user choose to use the first option of irrigation timing criteria in which the user specifies the dates and depth of water to be applied.

ISIAMod simulates daily biomass yield based on the relationship between photosynthetic active radiation (PAR) and the RUE (Yang *et al*., 2004). The PAR is computed based on the relationship between net solar radiation, leaf area index, and crop canopy extinction characteristics (Sharpley and Williams, 1990). The seasonal cumulative biomass yield is converted to harvestable yield by multiplying the biomass yield by the crop harvest index which is a crop parameter. The approach used by ISIAMod to simulate crop yield is similar to EPIC model (Williams *et al*., 1989).

ISIAMod program was written in FORTRAN 77 and compiled using FORTRAN PowerStation version 1.0F. A schematic diagram of the model showing the input and output variables, and the flow chart of the computer program are presented in Appendix 1 and 2, respectively. ISIAMod has been calibrated and validated for irrigated maize crop (TMV1-ST) for Mkoji sub-catchment of the Great Ruaha River basin in Tanzania using field experimental data (Igbadun, 2006). Table 1 shows the crop and soil parameters calibrated for the maize crop in Mkoji sub-catchment.

## 2.3 Procedure for Simulating and Evaluating Irrigation Scheduling Scenarios for the Maize Crop

The focus of this study was to understand the consequences of increasing the interval of irrigating maize crop beyond the conventional seven days that is practiced in Mkoji sub-catchment. Since there were no recommended water application depths (WAD) per irrigation for maize crop in the study area prior to this study, a field survey was first carried out to determine the range of WAD per irrigation in the farmers' field in IZTIS. The water application depths in 22 farmers' fields were monitored for six consecutive weeks using cutthroat flumes. A stopwatch was used to record the time taken to irrigate a known area in each farmer's field each time the farmer irrigates. The discharge measured from the flumes and the times recorded were used to establish the depths of water applied by the individual farmers.

Table 1. Crop and soil parameters calibrated for maize crop for the study area

| **Parameters** | **Value** |
|---|---|
| Maximum rooting depth | 1.2 m |
| Maximum harvest index | 0.34 |
| Harvest index adjustment factor for the flowering stage | 0.45 |
| Harvest index adjustment factor for the maturity stage | 0.50 |
| Radiation extinction coefficient | 0.55 |
| Maximum leaf area index | 0.35 $m^2/m^2$ |
| RUE (establishment and vegetative stages) | 0.25 g/MJ |
| RUE (flowering and maturity stages) | 0.23 g/MJ |
| Base temperature | $8^oC$ |
| Optimal temperature | $24^oC$ |
| Fraction of the growth duration at which leaf area index starts to decline | 0.75* |
| Days after planting at which establishment growth stage starts | 0* |
| Days after planting at which vegetative growth stage starts | 23* |
| Days after planting at which flowering growth stage starts | 64* |
| Days after planting at which maturity growth stage starts | 93* |
| Peak crop water use ($k_c$) coefficient | 1.2 |
| Soil dependent transpiration constant | 0.018 m/day |
| Evaporation coefficient for bare soil | 1.05 |

* = obtained from field experiments

ISIAMod was used to simulate crop and soil water balance responses for different irrigation scheduling scenarios. Two groups of irrigation scheduling scenarios were investigated. The first was increasing irrigation intervals from the conventional 7 days to 9, 10, 12, and 14 days at application depths of 30, 35, 40, 45, 50, 55, 60, 65, and 70 mm per irrigation. The second group of scheduling scenarios investigated was increasing the irrigation interval of one growth stage only at a time (either the vegetative, flowering or grain filling growth stage) from 7 to 9, 12, and 14 days, while maintaining a 7 days interval at the other growth stages. The water application depths observed under the second group of scheduling scenarios were 30, 35, 40, 45, 50, 60, and 70 mm. The range of water application depths observed in the two groups of scenario studies fall within the range of WAD observed at farmers' fields. In a series of field experiments to study the effects of deficit irrigation scheduling on crop water productivity of irrigated maize in Mkoji sub-catchment, Igbadun *et al.* (2006) tested some deficit irrigation scheduling options using 7 days and 14 days irrigation intervals at one or more growth stages of a maize crop. The yields reported in their study showed that it is possible to irrigated maize crop at 14-day interval from vegetative to grain filling stages in the Mkoji sub-catchment; although the grain yields reported for the 14 days irrigation interval were about one-third of what was obtained under the 7 days irrigation interval. The irrigation scheduling intervals observed in this study were randomly selected to fall within the 7 and 14 days intervals.

The method of irrigation considered in this study was surface. The scheduling scenarios simulated were based on total irrigation (no rainfall). Planting was assumed to be on well-leveled basins or at the base of close-ends short furrows of four to six metres long. Therefore, water applied was assumed to infiltrate into the soil without runoff. This was the method of irrigating maize in the study area. The simulation exercise for each of the irrigation scheduling options was carried out for five cropping seasons using weather data for five years (1985, 1991, 1993, 2001, and 2003) for the study area. These years were randomly selected from a pool of 16 years weather data in the study area to capture the years with very high, normal and low maximum and minimum temperatures during the crop growing season of July to October. A planting date of 20th July was assumed for all the simulation. The planting date selected was about the mid-period when maize which depends totally on irrigation from planting to maturity is planted in the study area. The soil input data used in the scenario studies is shown in Table 2. The impacts of the irrigation scheduling scenarios on crop response and soil water balance were evaluated with respect to the conventional 7-day irrigation interval. This was done by comparing the percentage losses/gains in yield, water applied, evapotranspiration and deep percolation between the 7 day irrigation interval for each WAD and those of extended interval of equivalent WAD.

Table 2. Soil physical properties of study area

| Soil profile depth (cm) | Moisture content at field capacity ($m^3/m^3$) | Moisture content at wilting point ($m^3/m^3$) | Soil bulk density (dry) ($g/cm^3$) | Soil bulk density at Field capacity ($g/cm^3$) | Clay % | Silt % | Sand % | Soil Textural Class |
|---|---|---|---|---|---|---|---|---|
| 0-15 | 0.283 | 0.122 | 1.38 | 1.65 | 33 | 15 | 52 | Sandy clay |
| 15-40 | 0.301 | 0.164 | 1.40 | 1.75 | 35 | 15 | 50 | Sandy clay |
| 40-70 | 0.312 | 0.215 | 1.41 | 1.65 | 35 | 13 | 52 | Sandy clay |
| 70-100 | 0.311 | 0.211 | 1.35 | 1.87 | 35 | 19 | 46 | Sand clay loam |

## 3. RESULTS AND DISCUSSION

### 3.1 Water Application Depth in Farmers' Fields

The field survey revealed that range of water application depths measured in the farmers' fields was between 25 and 70 mm. The average water application depths per farmers' field were ranked and grouped into class intervals of 5mm. Figure 1 shows the percentage of farmers irrigating in each class interval. The class interval of WAD with the highest percentage of farmers was the 60-64 mm, being 27.3%. This implies that more farmers irrigate maize crop at WAD of 60 to 64 mm per week in the study area. This agrees with the findings of de Jager and Kennedy (1996) who reported that for supply-driven flood or bucket irrigation in Western Free State in South Africa, water application depth of individual farmers generally exceeded 50 mm per week. De Jager and Kennedy (1996) noted that the water application rate of the small-scale low-input farmers was 12 mm and 80 mm for bi-daily and weekly irrigation, respectively.

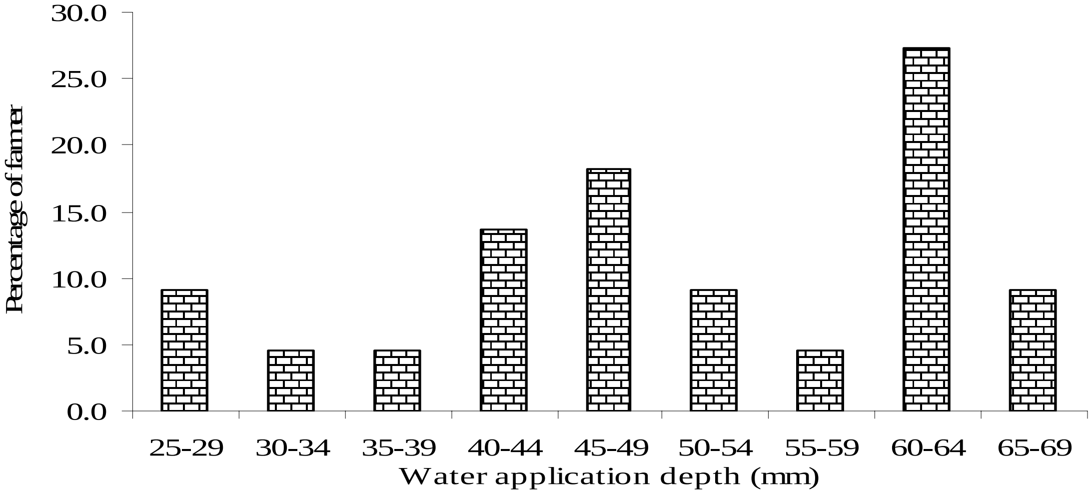


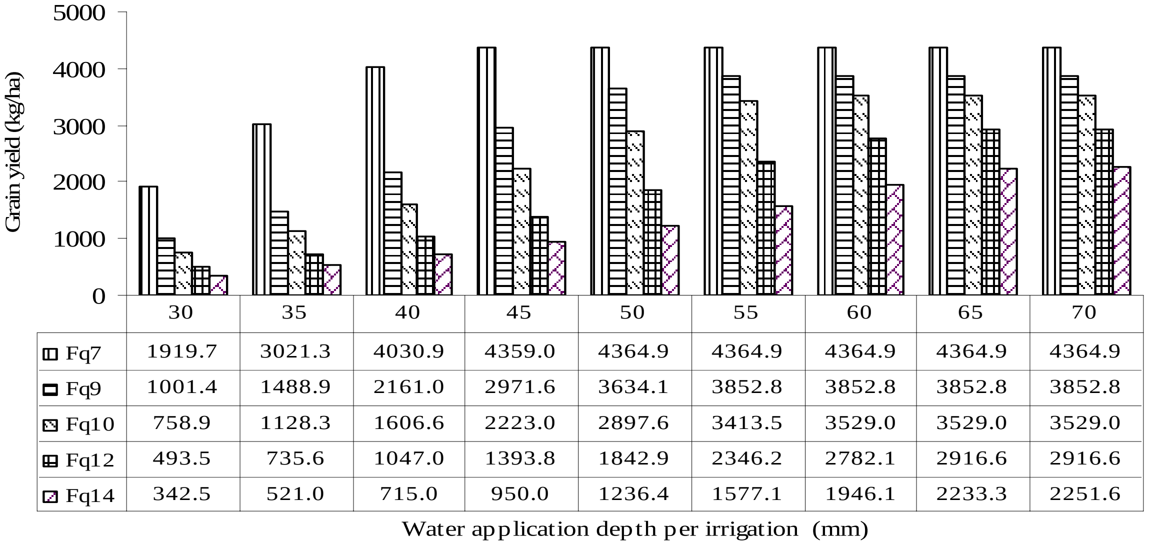
Figure 1. Percentage of farmers irrigating at the different water application depth

## 3.2 Effect of Increasing Irrigation Interval Above 7-Day on Yield and Soil Water Balance Responses

### 3.2.1 Simulated Grain Yield

Figure 2 shows the average simulated grain yields associated with the water application depths. The simulated grain yield ranged from about 340 kg/ha at 30 mm WAD per irrigation for a 14-day irrigation frequency to 4364 kg/ha obtained at 50 mm WAD per irrigation for a 7-day irrigation frequency. The grain yields simulated compared closely with grain yield reported for irrigated maize in the Mkoji sub-catchment. SWMRG- FAO (2003) and Igbadun *et al.* (2006) reported grain yields ranges of 1778 to 3703 kg/ha and 1580 to 3780 kg/ha, respectively, while (JICA/MAFS, 2002) reported a range of 1800 to 2000 kg/ha as average grain yield for irrigated maize in many of the irrigation schemes in the area.

Grain yield increased with increase in water application depth for the different intervals of irrigation until a peak grain yield value for each irrigation interval was reached. Thereafter, grain yields no longer response to increasing water application depth. The peak grain yields and the WAD at which peak yields were reached were not the same for the different irrigation intervals. The simulated peak grain yield for the 9- (Fq9), 10-(Fq10), 12-(Fq12) and 14-(Fq14) day irrigation intervals were all found to be lower than the 7-day irrigation interval. More so, grain yields decreased with increase in irrigation interval. The grain yields of the different irrigation intervals under the same level of WAD were consistently lower than the 7 day interval. Simulated grain yield under a 14-day irrigation frequency was less than 1000 kg/ha except when WAD per irrigation was beyond 45 mm.



| | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Fq7 | 1919.7 | 3021.3 | 4030.9 | 4359.0 | 4364.9 | 4364.9 | 4364.9 | 4364.9 | 4364.9 |
| Fq9 | 1001.4 | 1488.9 | 2161.0 | 2971.6 | 3634.1 | 3852.8 | 3852.8 | 3852.8 | 3852.8 |
| Fq10 | 758.9 | 1128.3 | 1606.6 | 2223.0 | 2897.6 | 3413.5 | 3529.0 | 3529.0 | 3529.0 |
| Fq12 | 493.5 | 735.6 | 1047.0 | 1393.8 | 1842.9 | 2346.2 | 2782.1 | 2916.6 | 2916.6 |
| Fq14 | 342.5 | 521.0 | 715.0 | 950.0 | 1236.4 | 1577.1 | 1946.1 | 2233.3 | 2251.6 |

Figure 2. Simulated grain yield for the different irrigation intervals

Table 3 shows the percentage reduction in simulated grain yields with reference to the 7-day irrigation scheduling. Increasing irrigation interval from 7 to 9 days reduced grain yield by about 11 to 51 % depending on the water application depth per irrigation. Increasing irrigation interval to 12 and 14 days resulted in yield reduction of between 33 and 74 % and between 48 and 82 %, respectively. The lower values in the ranges of yield reductions were those that occurred at higher WAD. That means the magnitude of grain yield reduction decreases as WAD increases. A comparison of the peak grain yields of the scheduling scenarios showed that the peak grain yields of the 9-, 10-, 12-, and 14-day irrigation intervals were lower than the 7-day irrigation interval by about 12, 19, 33, and 48 %, respectively.

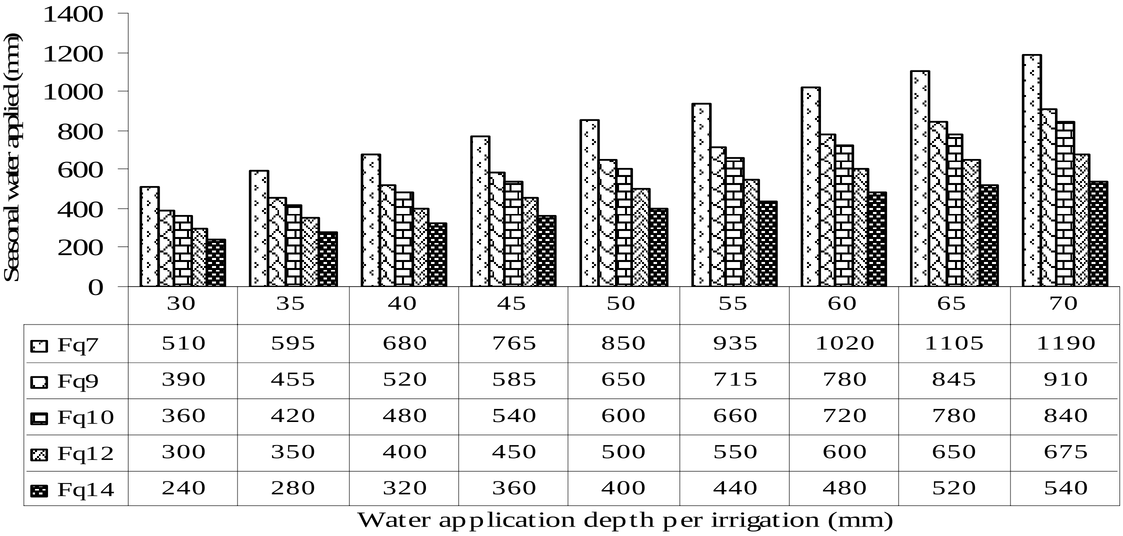
Table 3. Percent reduction in grain yield for the different interval of irrigation with reference to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Fq9 | 47.8 | 50.7 | 46.4 | 31.8 | 16.7 | 11.7 | 11.7 | 11.7 | 11.7 |
| Fq10 | 60.5 | 62.7 | 60.1 | 49.0 | 33.6 | 21.8 | 19.2 | 19.2 | 19.2 |
| Fq12 | 74.3 | 75.7 | 74.0 | 68.0 | 57.8 | 46.2 | 36.3 | 33.2 | 33.2 |
| Fq14 | 82.2 | 82.8 | 82.3 | 78.2 | 71.7 | 63.9 | 55.4 | 48.8 | 48.4 |

These results indicate that increasing the interval of irrigation for the maize crop beyond the conventional 7 days will lead to significant decrease in grain yield irrespective of the depth of water applied at irrigation. The maximum attainable yield under such extended interval of irrigation will be significantly less than what is obtainable under a 7-day irrigation frequency. If the maize crop is irrigated at 14 days interval throughout the crop growing season even at 70 mm WAD, the maximum attainable yield will be about half of what can be obtained under a 7-day irrigation frequency. The reason for the decrease in maximum attainable yield as the interval of irrigation increases can be attributed to the fact delaying irrigation for whatever number of days beyond the 7 days makes the crop to be subjected moisture stress before the next irrigation. The longer the number of days, the greater the moisture stresses imposed on the crop. The stresses consequently retard crop growth and development and maximum attainable yield. The trend of the results obtained from these irrigation scheduling scenario evaluations confirms Otegui *et al.*(1995) statements that maize is very sensitive to drought, and that it is very difficult to plan deficit irrigation for maize without causing yield reduction (Rhoades and Bennett, 1990; Lamm *et al.*, 1995).

### 3.2.2 Seasonal Water Applied

Figure 3 shows that the simulated seasonal water applied for the different irrigation scheduling scenarios. The simulated seasonal water applied varied from 240 mm (2400 $m^3$/ha) to 1190 mm (11900 $m^3$/ha), depending on the WAD and the frequency of irrigation, and the interval of irrigation. The simulated seasonal water applied to obtain peak grain yield under the 7 days irrigation interval was 850 mm, while 780 mm was applied under the 9 and 10 days irrigation intervals to obtain peak yields for the different irrigation intervals. The percent reduction in seasonal water applied ranged from about 24 % for the 9 days irrigation interval to about 53 % for the 14 days irrigation interval. The reason for the reductions was because the number of irrigation for the entire crop growing season was reduced as the interval of irrigation increased.

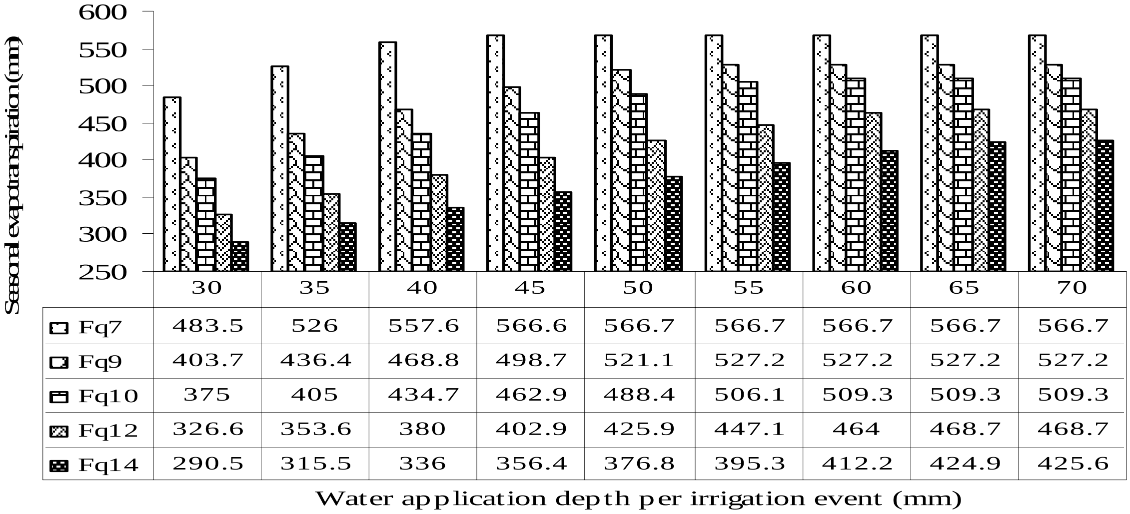


| | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| ▫ Fq7 | 510 | 595 | 680 | 765 | 850 | 935 | 1020 | 1105 | 1190 |
| ▫ Fq9 | 390 | 455 | 520 | 585 | 650 | 715 | 780 | 845 | 910 |
| ▤ Fq10 | 360 | 420 | 480 | 540 | 600 | 660 | 720 | 780 | 840 |
| ▨ Fq12 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 675 |
| ▩ Fq14 | 240 | 280 | 320 | 360 | 400 | 440 | 480 | 520 | 540 |

Figure 3. Seasonal water applied for the different irrigation scenarios.

### 3.2.3 Seasonal Evapotranspiration

Figure 4 shows the simulated seasonal evapotranspiration (SET) for the different irrigation intervals. The peak values of the SET and the WAD at which the peak values were attained were not the same for the different irrigation frequencies. The peak SET for the 7 day irrigation interval was 567 mm. This was attained at 45 mm WAD. The peak seasonal crop water use for the 14 days irrigation interval was 425 mm and was attained when water was applied at 65 mm per irrigation. The simulated peak seasonal evapotranspiration for the 7-, 9-, 10-, and 12-day intervals fells within the range of seasonal water consumption for maize given by Howell et al. (1998) being 465-802 mm. The SET for the 14-day interval were below treatments Howell et al's range. This implies that the scheduling interval under irrigate the crop, and that explains why the yields were low.



| | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Fq7 | 483.5 | 526 | 557.6 | 566.6 | 566.7 | 566.7 | 566.7 | 566.7 | 566.7 |
| Fq9 | 403.7 | 436.4 | 468.8 | 498.7 | 521.1 | 527.2 | 527.2 | 527.2 | 527.2 |
| Fq10 | 375 | 405 | 434.7 | 462.9 | 488.4 | 506.1 | 509.3 | 509.3 | 509.3 |
| Fq12 | 326.6 | 353.6 | 380 | 402.9 | 425.9 | 447.1 | 464 | 468.7 | 468.7 |
| Fq14 | 290.5 | 315.5 | 336 | 356.4 | 376.8 | 395.3 | 412.2 | 424.9 | 425.6 |

Figure 4. Simulated seasonal evapotranspiration for the different irrigation intervals

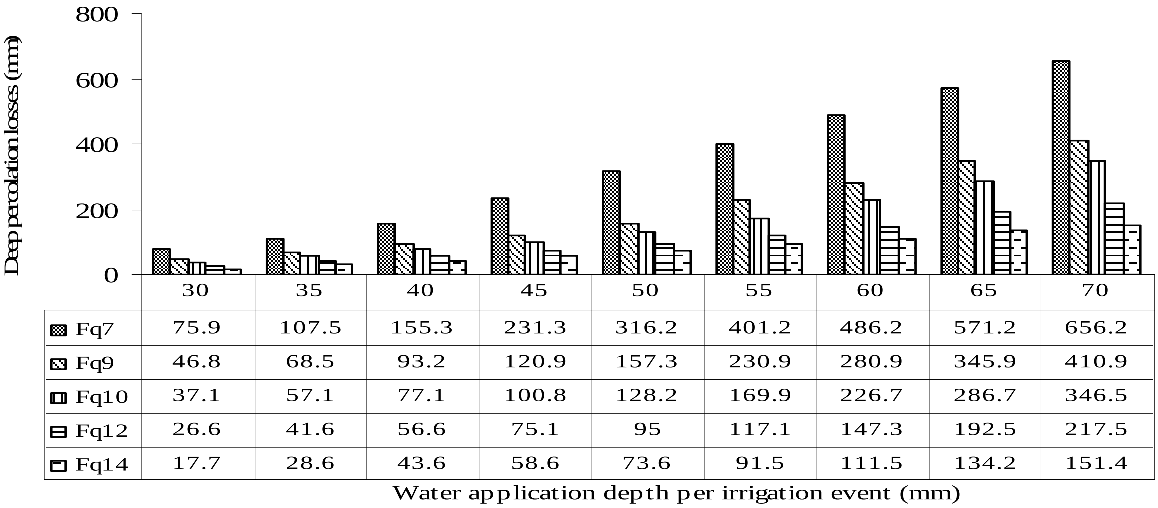
Table 4 presents the percent reduction in seasonal evapotranspiration due to the increase in irrigation intervals. The trend of the percentage reduction results suggest that seasonal evapotranspiration can be improved by irrigating above 45 mm WAD per irrigation if the interval of irrigation is to be increased beyond 7 days. However, irrespective of the WAD, the maximum attainable evapotranspiration under such irrigation scheduling will be less than that obtainable at 7-day irrigation frequency. The reason for this can be attributed to moisture stress that occurs when irrigation is delayed some days beyond the 7 days. Moisture stress retarded crop growth and development which in turn affect the crop water uptake (Kato *et al.*, 2004).

Table 4. Percentage reduction in seasonal crop water use for the different interval of irrigation with reference to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Fq9 | 16.50 | 17.03 | 15.93 | 11.98 | 8.05 | 6.97 | 6.97 | 6.97 | 6.97 |
| Fq10 | 22.44 | 23.00 | 22.04 | 18.30 | 13.82 | 10.69 | 10.13 | 10.13 | 10.13 |
| Fq12 | 32.45 | 32.78 | 31.85 | 28.89 | 24.85 | 21.10 | 18.12 | 17.29 | 17.29 |
| Fq14 | 39.92 | 40.02 | 39.74 | 37.10 | 33.51 | 30.25 | 27.26 | 25.02 | 24.90 |

### 3.2.4 Deep Percolation

Figure 5 shows the simulated seasonal deep percolation under the different irrigation scheduling intervals under evaluation. The seasonal deep percolation ranged from 17.7 mm (177 $m^3$/ha) to 656.2 mm (6562 $m^3$/ha) depending on the WAD and the frequency of irrigation. Table 5 shows the percentage reduction in seasonal deep percolation when the irrigation interval is extended beyond 7 days.



| | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| ▩ Fq7 | 75.9 | 107.5 | 155.3 | 231.3 | 316.2 | 401.2 | 486.2 | 571.2 | 656.2 |
| ▧ Fq9 | 46.8 | 68.5 | 93.2 | 120.9 | 157.3 | 230.9 | 280.9 | 345.9 | 410.9 |
| ▥ Fq10 | 37.1 | 57.1 | 77.1 | 100.8 | 128.2 | 169.9 | 226.7 | 286.7 | 346.5 |
| ▤ Fq12 | 26.6 | 41.6 | 56.6 | 75.1 | 95 | 117.1 | 147.3 | 192.5 | 217.5 |
| ▭ Fq14 | 17.7 | 28.6 | 43.6 | 58.6 | 73.6 | 91.5 | 111.5 | 134.2 | 151.4 |

Figure 5. Simulated seasonal deep percolation for the different irrigation intervals

Table 5. Percentage reduction in deep percolation for the different irrigation intervals with reference to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Fq9 | 38.34 | 36.28 | 39.99 | 47.73 | 50.25 | 42.44 | 42.22 | 39.44 | 37.38 |
| Fq10 | 51.12 | 46.88 | 50.35 | 56.42 | 59.46 | 57.66 | 53.38 | 49.81 | 47.20 |
| Fq12 | 64.95 | 61.30 | 63.55 | 67.53 | 69.96 | 70.81 | 69.71 | 66.30 | 66.85 |
| Fq14 | 76.68 | 73.40 | 71.93 | 74.66 | 76.72 | 77.19 | 77.06 | 76.51 | 76.93 |

### 3.2.5 Crop Water Productivity

Table 6 shows the simulated crop water productivity in terms of water applied to grow the crop ($CWP_{(wa)}$) and crop consumptive use ($CWP_{(cu)}$), respectively. The highest value of $CWP_{(wa)}$ under the 9 days irrigation interval was at 50 mm WAD, while under a 10-day irrigation frequency, the highest $CWP_{(wu)}$ was obtained at 55 WAD. More so, the crop water productivity in terms of crop consumptive use ($CWP_{(wu)}$) for the 9- and 10-day irrigation frequencies at the 50 and 55 WAD, respectively compared favourably with those obtained under 7-day frequency. The pattern of the crop water productivity results further buttress the fact that the 9- and 10-day irrigation frequencies are the optimal irrigation schedules when there is the need to increase irrigation interval beyond the regular 7 days.

The implication of the overall results is that when irrigation interval is extended beyond 7 days, seasonal irrigation water applied and the associated deep percolation losses will be reduced significantly. However, grain yield losses due to increase in interval of irrigation beyond 7 days will also be significantly high. The optimal schedule which minimized grain yield and crop consumptive use reduction while maximizing deep percolation reductions seems to be a 9-day irrigation interval at 50 mm WAD per irrigation and a 10-day irrigation interval at 55 mm WAD. Yield losses associated with these two scheduling options were only 17 and 22 % for the 9 and 10-day frequencies, respectively. The reduction in seasonal crop water use was only 8 and 11 %, while deep percolation was reduced by 50 and 58 % for the 9- and 10-day irrigation interval, respectively.

Table 6. Crop water productivity in terms of water applied

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
|---|---|---|---|---|---|---|---|---|---|
| Crop water productivity in terms of water applied (kg/m$^3$) | | | | | | | | | |
| Fq7 | 0.38 | 0.51 | 0.59 | 0.57 | 0.51 | 0.47 | 0.43 | 0.40 | 0.37 |
| Fq9 | 0.26 | 0.33 | 0.42 | 0.51 | 0.56 | 0.49 | 0.49 | 0.46 | 0.42 |
| Fq10 | 0.21 | 0.27 | 0.33 | 0.41 | 0.48 | 0.52 | 0.49 | 0.45 | 0.42 |
| Fq12 | 0.16 | 0.21 | 0.26 | 0.31 | 0.37 | 0.43 | 0.46 | 0.45 | 0.43 |
| Fq14 | 0.14 | 0.19 | 0.22 | 0.26 | 0.31 | 0.36 | 0.41 | 0.43 | 0.42 |
| Crop water productivity in terms of crop consumptive use (kg/m$^3$) | | | | | | | | | |
| Fq7 | 0.40 | 0.57 | 0.72 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 |
| Fq9 | 0.25 | 0.34 | 0.46 | 0.60 | 0.70 | 0.73 | 0.73 | 0.73 | 0.73 |
| Fq10 | 0.20 | 0.28 | 0.37 | 0.48 | 0.59 | 0.67 | 0.69 | 0.69 | 0.69 |
| Fq12 | 0.15 | 0.21 | 0.28 | 0.35 | 0.43 | 0.52 | 0.60 | 0.62 | 0.62 |
| Fq14 | 0.12 | 0.17 | 0.21 | 0.27 | 0.33 | 0.40 | 0.47 | 0.53 | 0.53 |

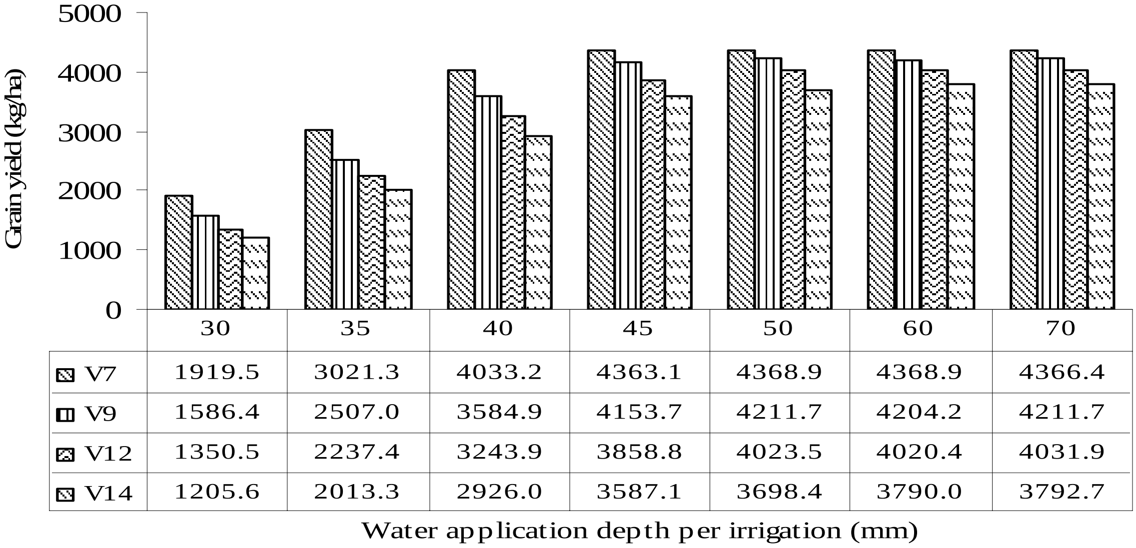
## 3.3 Effect of Increasing the Interval of Irrigation beyond 7 Days at only One Crop Growth Stage on Crop Yield and Soil Water Balance Responses

### 3.3.1 Grain Yield

Figures 6 (a-c) present the simulated grain yield associated with the different irrigation intervals at the vegetative, flowering and grain filling stages, respectively. The interval of irrigation evaluated were 9, 12, and 14 days only, while the 7 days interval was used as reference for quantifying the effect of the irrigation interval on yield and water responses.

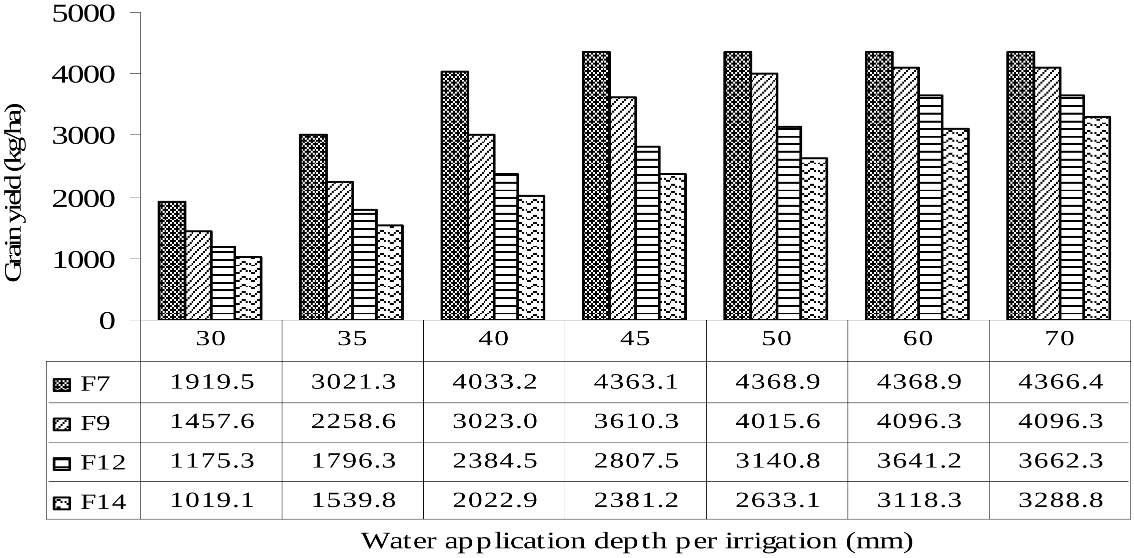
The pattern of increase in grain yield was similar for the three growth stages. Grain yield increased with increased in WAD up to a peak value, and this peak value depend on the frequency of irrigation, water application depth and the crop growth stage. The 7 days irrigation interval recorded the highest grain yield while the 14 days interval recorded the lowest yield in the three growth stages. The trend of the result also implies that when irrigation interval is extended beyond 7 days at either the vegetative, flowering or grain filling stages, grain yield falls below what is obtainable at 7 days irrigation interval irrespective of the water application depth per irrigation. The magnitude of yield reduction associated with the irrigation schedules for the different growth stages is presented in Table 7.

At the vegetative stage, the reduction in grain yield associated with the irrigation intervals ranged from about 4 to 37 %, while at flowering, yield reduction ranged from about 6 to 47 %. At grain filling, yield reduction due to the irrigation intervals ranged from 3 to 28 %. The magnitude of yield reduction in any growth stage increased with increase in irrigation interval and decreased with increased in WAD. This was expected since the lower the WAD per irrigation, the less water is available in the plant root zone; and the longer the interval between successive irrigations, the less water available for crop use. This consequently leads to moisture stress which reduces grain yield.



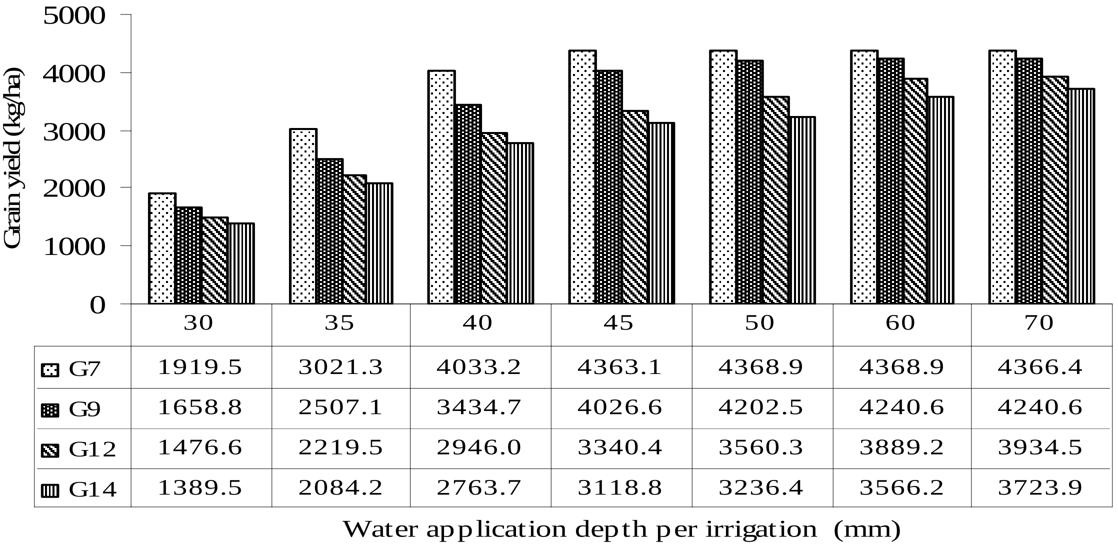
| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▧ V7 | 1919.5 | 3021.3 | 4033.2 | 4363.1 | 4368.9 | 4368.9 | 4366.4 |
| ▥ V9 | 1586.4 | 2507.0 | 3584.9 | 4153.7 | 4211.7 | 4204.2 | 4211.7 |
| ▨ V12 | 1350.5 | 2237.4 | 3243.9 | 3858.8 | 4023.5 | 4020.4 | 4031.9 |
| ▨ V14 | 1205.6 | 2013.3 | 2926.0 | 3587.1 | 3698.4 | 3790.0 | 3792.7 |

Figure 6 (a). Simulated grain yields for the 7, 9, 12, and 14 days irrigation scheduling intervals for the vegetative (V) growth stage.



| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▩ F7 | 1919.5 | 3021.3 | 4033.2 | 4363.1 | 4368.9 | 4368.9 | 4366.4 |
| ▨ F9 | 1457.6 | 2258.6 | 3023.0 | 3610.3 | 4015.6 | 4096.3 | 4096.3 |
| ▤ F12 | 1175.3 | 1796.3 | 2384.5 | 2807.5 | 3140.8 | 3641.2 | 3662.3 |
| ▨ F14 | 1019.1 | 1539.8 | 2022.9 | 2381.2 | 2633.1 | 3118.3 | 3288.8 |

Figure 6 (b). Simulated grain yields for the 7, 9, 12, and 14 days irrigation scheduling intervals for the flowering (F) growth stages.



| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▦ G7 | 1919.5 | 3021.3 | 4033.2 | 4363.1 | 4368.9 | 4368.9 | 4366.4 |
| ▩ G9 | 1658.8 | 2507.1 | 3434.7 | 4026.6 | 4202.5 | 4240.6 | 4240.6 |
| ▧ G12 | 1476.6 | 2219.5 | 2946.0 | 3340.4 | 3560.3 | 3889.2 | 3934.5 |
| ▥ G14 | 1389.5 | 2084.2 | 2763.7 | 3118.8 | 3236.4 | 3566.2 | 3723.9 |

Figure 6 (c). Simulated grain yields for the 7, 9, 12, and 14 days irrigation scheduling intervals for the grain filling (G) growth stages.

Table 7. Percent reduction in grain yield for the various irrigation scheduling intervals with respect to the 7 days irrigation interval

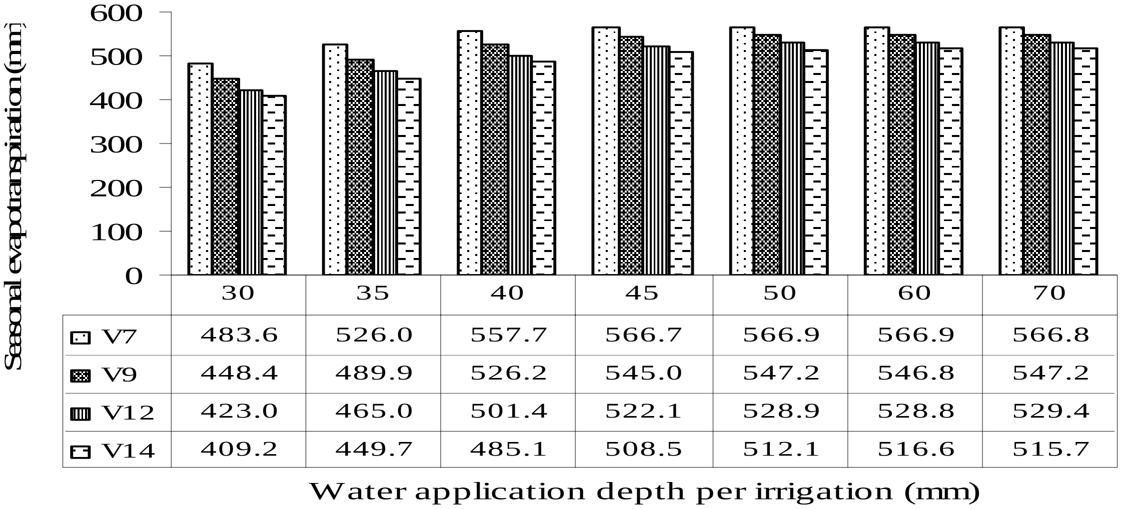
| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| | | | Vegetative | | | | |
| V9 | 17.35 | 17.02 | 11.12 | 4.80 | 3.60 | 3.77 | 3.54 |
| V12 | 29.64 | 25.95 | 19.57 | 11.56 | 7.91 | 7.98 | 7.66 |
| V14 | 37.19 | 33.36 | 27.45 | 17.79 | 15.35 | 13.25 | 13.14 |
| | | | Flowering | | | | |
| F9 | 24.06 | 25.24 | 25.05 | 17.25 | 8.09 | 6.24 | 6.19 |
| F12 | 38.77 | 40.55 | 40.88 | 35.65 | 28.11 | 16.66 | 16.13 |
| F14 | 46.91 | 49.03 | 49.84 | 45.42 | 39.73 | 28.63 | 24.68 |
| | | | Grain filling | | | | |
| G9 | 13.58 | 17.02 | 14.84 | 7.71 | 3.81 | 2.94 | 2.88 |
| G12 | 23.07 | 26.54 | 26.96 | 23.44 | 18.51 | 10.98 | 9.89 |
| G14 | 27.61 | 31.02 | 31.48 | 28.52 | 25.92 | 18.37 | 14.71 |

A comparison of yield reductions across the three growth stages showed that for the same level of WAD and interval of irrigation, the flowering growth stage recorded the highest reduction in grain yield. The differences in yield reduction between the flowering and vegetative stages and between the flowering and the grain filling stages was of the order of ratio 2:1 and 3:2, respectively. This implies that for the same level of WAD and same interval of irrigation, yield loss at the flowering stage was about twice that of the vegetative stage, and about one and half times that of the grain filling stage. Therefore, it can be said that the flowering growth stage (defined as tasseling initiation to silking in this study) is the most critical to irrigation scheduling for the maize crop in this study. This finding also agrees with some literature reports that have identified the tasseling to silking stage of the maize crop as the most critical for irrigation (Pandey *et al.*, 2000; Tarimo *et al.*, 2004). The grain filling stage was also noticed to be more prone to yield decrease with increase in irrigation interval compared to the vegetative stage, but only when the interval of irrigation exceeded 9 days. For the same level of WAD at irrigation interval of 9 days, the difference in yield reduction between the grain filling and the vegetative stage was less than 5 %.

### 3.3.2 Seasonal Evapotranspiration

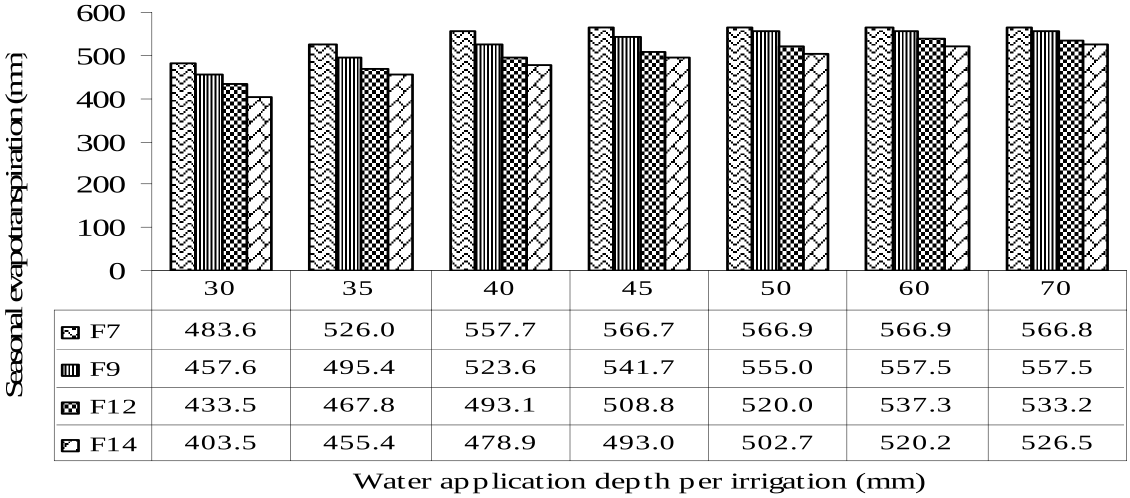
The seasonal evapotranspiration (SET) of the maize crop for the different scheduling scenarios in the vegetative, flowering and grain filling growth stages are presented in Figs. 7 (a-c), respectively. The SET had similar trend with the grain yield, with the 7 days interval recording the highest SET and the 14 days interval recording the lowest SET in all of the three growth stages. More so, SET decreased with increased in irrigation interval in any of the three growth stages.

Table 8 shows the percent deficit in SET (SETd) for the different scheduling scenarios for the three growth stages. These deficits were computed with respect to the seasonal evapotranspiration of the 7 days irrigation interval scenario. The SET deficit represents the magnitude of the seasonal moisture stress that the crop was subjected to, and subsequently led to yield losses (Doorenbos and Kassam, 1979.As expected, the magnitude of the SET deficits decreased with increase in WAD since the depth of water that can be made available for crop use increased with increase in WAD.



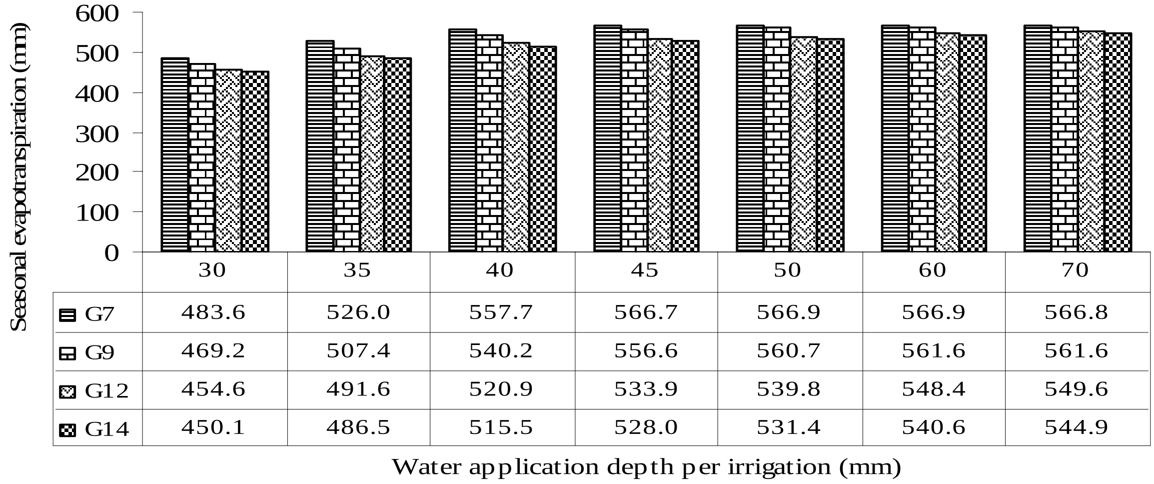
| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| V7 | 483.6 | 526.0 | 557.7 | 566.7 | 566.9 | 566.9 | 566.8 |
| V9 | 448.4 | 489.9 | 526.2 | 545.0 | 547.2 | 546.8 | 547.2 |
| V12 | 423.0 | 465.0 | 501.4 | 522.1 | 528.9 | 528.8 | 529.4 |
| V14 | 409.2 | 449.7 | 485.1 | 508.5 | 512.1 | 516.6 | 515.7 |

Figure 7 (a). Simulated seasonal evapotranspiration for the different irrigation schedules at vegetative stage (V) growth stage.



|  | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| F7 | 483.6 | 526.0 | 557.7 | 566.7 | 566.9 | 566.9 | 566.8 |
| F9 | 457.6 | 495.4 | 523.6 | 541.7 | 555.0 | 557.5 | 557.5 |
| F12 | 433.5 | 467.8 | 493.1 | 508.8 | 520.0 | 537.3 | 533.2 |
| F14 | 403.5 | 455.4 | 478.9 | 493.0 | 502.7 | 520.2 | 526.5 |

Figure 7 (b). Simulated seasonal evapotranspiration for the different irrigation schedules at flowering (F) growth stages.



|  | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| G7 | 483.6 | 526.0 | 557.7 | 566.7 | 566.9 | 566.9 | 566.8 |
| G9 | 469.2 | 507.4 | 540.2 | 556.6 | 560.7 | 561.6 | 561.6 |
| G12 | 454.6 | 491.6 | 520.9 | 533.9 | 539.8 | 548.4 | 549.6 |
| G14 | 450.1 | 486.5 | 515.5 | 528.0 | 531.4 | 540.6 | 544.9 |

Figure 7 (c). Simulated seasonal evapotranspiration for the different irrigation schedules at grain filling (G) stages.

A comparison of the SETd with the corresponding yield reduction (Table 7) indicated that the effect of SETD on grain yield did not depend only on its magnitude, but also on the crop growth stage at which it occurred. Grain yield was reduced by 50 % at flowering stage due to SETd of about 14 % (Scenario F14, 40 mm WAD), but a 13 % SETd at vegetative stage (Scenario V14, 40 mm WAD) only resulted to a yield reduction of about 28 %. More so, a SETd of about 7 % resulted to about 23 % yield reduction at grain filling (Scenario G12, 45 mm WAD), while SETd of about 7 % resulted to only 11 % yield reduction at vegetative stage (V12, 45 mm WAD).

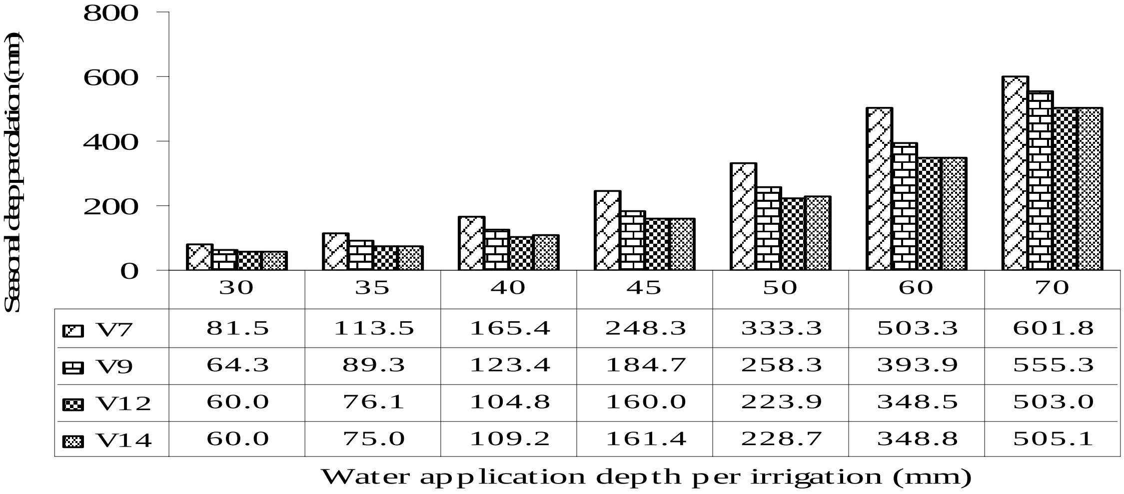
Table 8. Percent reduction in seasonal evapotranspiration for the various irrigation scheduling intervals with respect to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| | | | Vegetative | | | | |
| V9 | 7.28 | 6.86 | 5.65 | 3.83 | 3.48 | 3.54 | 3.46 |
| V12 | 12.53 | 11.60 | 10.10 | 7.87 | 6.70 | 6.71 | 6.60 |
| V14 | 15.38 | 14.51 | 13.02 | 10.27 | 9.67 | 8.86 | 9.01 |
| | | | Flowering | | | | |
| F9 | 5.38 | 5.82 | 6.11 | 4.41 | 2.10 | 1.66 | 1.64 |
| F12 | 10.36 | 11.06 | 11.58 | 10.22 | 8.27 | 5.22 | 5.93 |
| F14 | 16.56 | 13.42 | 14.13 | 13.01 | 11.32 | 8.24 | 7.11 |
| | | | Grain filling | | | | |
| G9 | 2.98 | 3.54 | 3.14 | 1.78 | 1.09 | 0.93 | 0.92 |
| G12 | 6.00 | 6.54 | 6.60 | 5.79 | 4.78 | 3.26 | 3.03 |
| G14 | 6.93 | 7.51 | 7.57 | 6.83 | 6.26 | 4.64 | 3.86 |

### 3.3.4 Deep Percolation

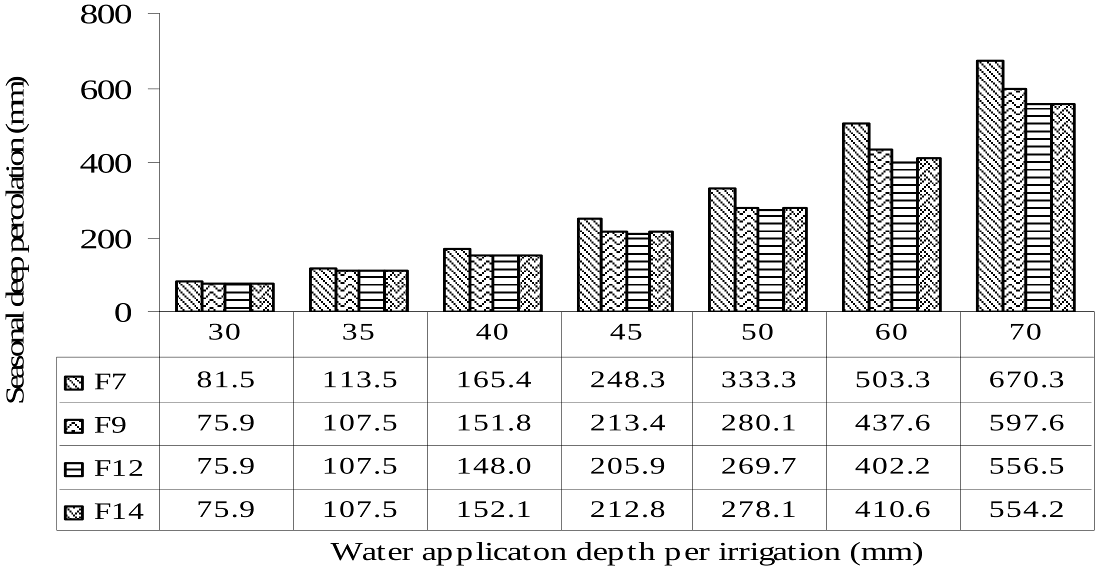
Figures 8 (a-c) show the simulated seasonal deep percolation for the irrigation scheduling scenarios of the vegetative, flowering and grain filling stages, respectively. The trend of deep percolation was similar for the scheduling scenarios of the three growth stages. The magnitude of deep percolation increased with increased in WAD as was expected. However, the amount of deep percolation for the 12 and 14 days irrigation intervals for the same level of WAD were about the same values in any growth stage.

Table 9 presents the percent reduction in deep percolation for the different scheduling scenarios. The percent reduction in deep percolation was highest at vegetative stage. A comparison of the differences in percent reduction of deep percolation among the three growth stages indicates that deep percolation was reduced by about 15 to 20 % when the interval of irrigation was increased at vegetative growth stage compared to flowering and grain filling. This meant that there was 15-20 % save of water that would have been loss to deep percolation when the irrigation interval was increased beyond 7 days at vegetative compared to the flowering and grain filling growth stages.



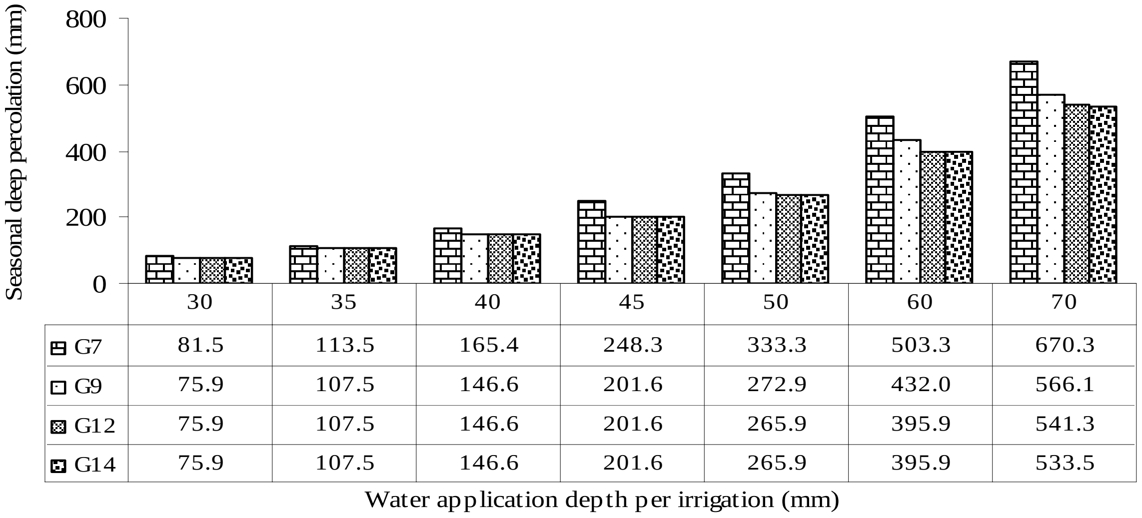
| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▨ V7 | 81.5 | 113.5 | 165.4 | 248.3 | 333.3 | 503.3 | 601.8 |
| ▤ V9 | 64.3 | 89.3 | 123.4 | 184.7 | 258.3 | 393.9 | 555.3 |
| ▩ V12 | 60.0 | 76.1 | 104.8 | 160.0 | 223.9 | 348.5 | 503.0 |
| ▦ V14 | 60.0 | 75.0 | 109.2 | 161.4 | 228.7 | 348.8 | 505.1 |

Figure 8 (a). Simulated deep percolation for the different irrigation scheduling intervals at vegetative (V) growth stage



| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▧ F7 | 81.5 | 113.5 | 165.4 | 248.3 | 333.3 | 503.3 | 670.3 |
| ▨ F9 | 75.9 | 107.5 | 151.8 | 213.4 | 280.1 | 437.6 | 597.6 |
| ▤ F12 | 75.9 | 107.5 | 148.0 | 205.9 | 269.7 | 402.2 | 556.5 |
| ▦ F14 | 75.9 | 107.5 | 152.1 | 212.8 | 278.1 | 410.6 | 554.2 |

Figure 8 (b). Simulated deep percolation for the different irrigation scheduling intervals at flowering (F) growth stage



| | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| ▤ G7 | 81.5 | 113.5 | 165.4 | 248.3 | 333.3 | 503.3 | 670.3 |
| ☐ G9 | 75.9 | 107.5 | 146.6 | 201.6 | 272.9 | 432.0 | 566.1 |
| ▩ G12 | 75.9 | 107.5 | 146.6 | 201.6 | 265.9 | 395.9 | 541.3 |
| ▦ G14 | 75.9 | 107.5 | 146.6 | 201.6 | 265.9 | 395.9 | 533.5 |

Figure 8 (c). Simulated deep percolation for the different irrigation scheduling intervals at grain filling (G) growth stage

Table 9. Percent reduction in seasonal deep percolation for the various irrigation scheduling intervals with respect to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| | | | Vegetative | | | | |
| V9 | 21.10 | 21.32 | 25.39 | 25.61 | 22.50 | 21.75 | 7.73 |
| V12 | 26.38 | 32.95 | 36.64 | 35.56 | 32.82 | 30.77 | 16.42 |
| V14 | 26.38 | 33.92 | 33.98 | 35.00 | 31.38 | 30.70 | 16.07 |
| | | | Flowering | | | | |
| F9 | 6.87 | 5.29 | 8.22 | 14.06 | 15.98 | 13.05 | 10.85 |
| F12 | 6.87 | 5.29 | 10.52 | 17.08 | 19.08 | 20.09 | 16.98 |
| F14 | 6.87 | 26.26 | 8.04 | 14.30 | 16.56 | 18.42 | 17.32 |
| | | | Grain filling | | | | |
| G9 | 6.87 | 5.29 | 11.37 | 18.81 | 18.12 | 14.17 | 15.55 |
| G12 | 6.87 | 5.29 | 11.37 | 18.81 | 20.22 | 21.34 | 19.25 |
| G14 | 6.87 | 5.29 | 11.37 | 18.81 | 20.22 | 21.34 | 20.41 |

### 1.1.1 3.3.5 Crop Water Productivity

Tables 10 and 11 shows the simulated crop water productivity in terms of water applied ($CWP_{(wa)}$) and crop consumptive use ($CWP_{(cu)}$), respectively. In the three growth stages, $CWP_{(wa)}$ increased with increase in WAD to a peak at 45 mm WAD and thereafter declined. This implies that for the different scheduling intervals in each growth stages, irrigating the maize crop at 45 mm WAD had a better utilization of seasonal water applied to the field. The trends of crop water productivity in terms of crop consumptive use ($CWP_{(wa)}$) also differed with respect to irrigation interval for the growth stages.

Table 10. Crop water productivity in terms of water applied ($CWP_{(wa)}$) for the various irrigation scheduling intervals with respect to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| | | | Vegetative | | | | |
| V7 | 0.38 | 0.51 | 0.59 | 0.57 | 0.51 | 0.43 | 0.37 |
| V9 | 0.35 | 0.48 | 0.60 | 0.62 | 0.56 | 0.47 | 0.40 |
| V12 | 0.32 | 0.46 | 0.58 | 0.61 | 0.57 | 0.48 | 0.41 |
| V14 | 0.29 | 0.41 | 0.52 | 0.57 | 0.53 | 0.45 | 0.39 |
| | | | Flowering | | | | |
| F7 | 0.38 | 0.51 | 0.59 | 0.57 | 0.51 | 0.43 | 0.37 |
| F9 | 0.35 | 0.45 | 0.54 | 0.56 | 0.53 | 0.44 | 0.38 |
| F12 | 0.33 | 0.42 | 0.49 | 0.49 | 0.47 | 0.43 | 0.37 |
| F14 | 0.31 | 0.40 | 0.46 | 0.46 | 0.43 | 0.40 | 0.35 |
| | | | Grain filling | | | | |
| G7 | 0.38 | 0.51 | 0.59 | 0.57 | 0.51 | 0.43 | 0.37 |
| G9 | 0.30 | 0.40 | 0.47 | 0.50 | 0.50 | 0.43 | 0.37 |
| G12 | 0.26 | 0.34 | 0.40 | 0.42 | 0.42 | 0.40 | 0.35 |
| G14 | 0.23 | 0.29 | 0.34 | 0.35 | 0.35 | 0.35 | 0.31 |

Table 11. Crop water productivity in terms of crop consumptive use ($CWP_{(cu)}$) for the various irrigation scheduling intervals with respect to the 7 days irrigation interval

| WAD (mm) | 30 | 35 | 40 | 45 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| | | | Vegetative | | | | |
| V7 | 0.40 | 0.57 | 0.72 | 0.77 | 0.77 | 0.77 | 0.77 |
| V9 | 0.35 | 0.51 | 0.68 | 0.76 | 0.77 | 0.77 | 0.77 |
| V12 | 0.32 | 0.48 | 0.65 | 0.74 | 0.76 | 0.76 | 0.76 |
| V14 | 0.29 | 0.45 | 0.60 | 0.71 | 0.72 | 0.73 | 0.74 |
| | | | Flowering | | | | |
| F7 | 0.40 | 0.57 | 0.72 | 0.77 | 0.77 | 0.77 | 0.77 |
| F9 | 0.35 | 0.49 | 0.64 | 0.72 | 0.75 | 0.76 | 0.76 |
| F12 | 0.32 | 0.45 | 0.57 | 0.63 | 0.66 | 0.71 | 0.72 |
| F14 | 0.31 | 0.43 | 0.54 | 0.59 | 0.61 | 0.66 | 0.68 |
| | | | Grain filling | | | | |
| G7 | 0.40 | 0.57 | 0.72 | 0.77 | 0.77 | 0.77 | 0.77 |
| G9 | 0.32 | 0.46 | 0.58 | 0.67 | 0.72 | 0.73 | 0.73 |
| G12 | 0.27 | 0.38 | 0.48 | 0.55 | 0.60 | 0.68 | 0.69 |
| G14 | 0.24 | 0.34 | 0.42 | 0.48 | 0.52 | 0.60 | 0.62 |

At vegetative stage, the 7 days irrigation interval scenario had better $CWP_{(wa)}$ only at 30 and 35 mm WAD while the 9 and 12 days irrigation intervals scenarios had better $CWP_{(wa)}$ between 40 mm and 50 mm WAD. The values of $CWP_{(wa)}$ at WAD above 50 mm were relative the same for the four irrigation intervals, and were lower than the values obtained at 40 to 50 mm WAD.

At flowering stage, $CWP_{(wa)}$ decreased with increase in irrigation interval. But when WAD per irrigation exceeded 50 mm, $CWP_{(wa)}$ became relatively the same for the different intervals of irrigation.. The trend of crop water productivity in terms of crop consumptive use ($CWP_{(cu)}$)

for the different scheduling scenarios in the vegetative and flowering stages were very similar. Better $CWP_{(cu)}$ were achieved only at 40 and 45 mm WAD and for the 7 and 9 days irrigation interval. These results implies that $CWP_{(wa)}$ can be improved by increasing the interval of irrigation at vegetative stage from 7 days to 9 to 12 days with water application depths of 40 to 50 mm. When the interval of irrigation is extending beyond 7 days to 9 days at flowering growth stage, $CWP_{(wa)}$ achieved will only match that of 7 days irrigation interval when water is applied at 45 to 50 mm depth. $CWP_{(wa)}$ in terms of water applied cannot be improved by increasing the interval of irrigation beyond 7 days at grain filling stage of the maize crop in the study area.

## 4. CONCLUSION

Crop yield, soil water balance, and crop water productivity responses to increase in irrigation interval beyond the conventional practice of 7 days for the maize crop in Mkoji sub-catchment was simulated using a computer-based simulation model. The evaluation of the simulated results indicated that irrigating the maize crop at intervals beyond 7 days, whether throughout the entire crop growing season or at some growth stages of the maize crop, leads to significant reduction in seasonal water applied in the field and the associated deep percolation losses. However, grain yield losses are also significantly high. If the maize crop is irrigated at 14 days interval throughout the crop growing season even at 70 mm WAD, the maximum attainable yield will be about half of what can be obtained under a 7-day irrigation frequency.

The optimal schedule which minimized grain yield and crop consumptive use reductions and maximizing deep percolation reductions was the 9-day irrigation interval at 50 mm WAD per irrigation and a 10-day irrigation interval at 55 mm WAD. Yield losses associated with these two scheduling options were only 17 and 22 % for the 9 and 10-day frequencies, respectively. The reduction in seasonal crop water use was only 8 and 11 %, while deep percolation was reduced by 50 and 58 % for the 9- and 10-day irrigation interval, respectively. The irrigation scheduling scenarios evaluated showed a feasibility of reducing the water supply for irrigation and an appealing tradeoff between yield reductions and water saved. However, whether irrigation farmers who are always profit-oriented can be convinced to accept such tradeoff remains a challenge that water resource managers and watershed stakeholders need to surmount.

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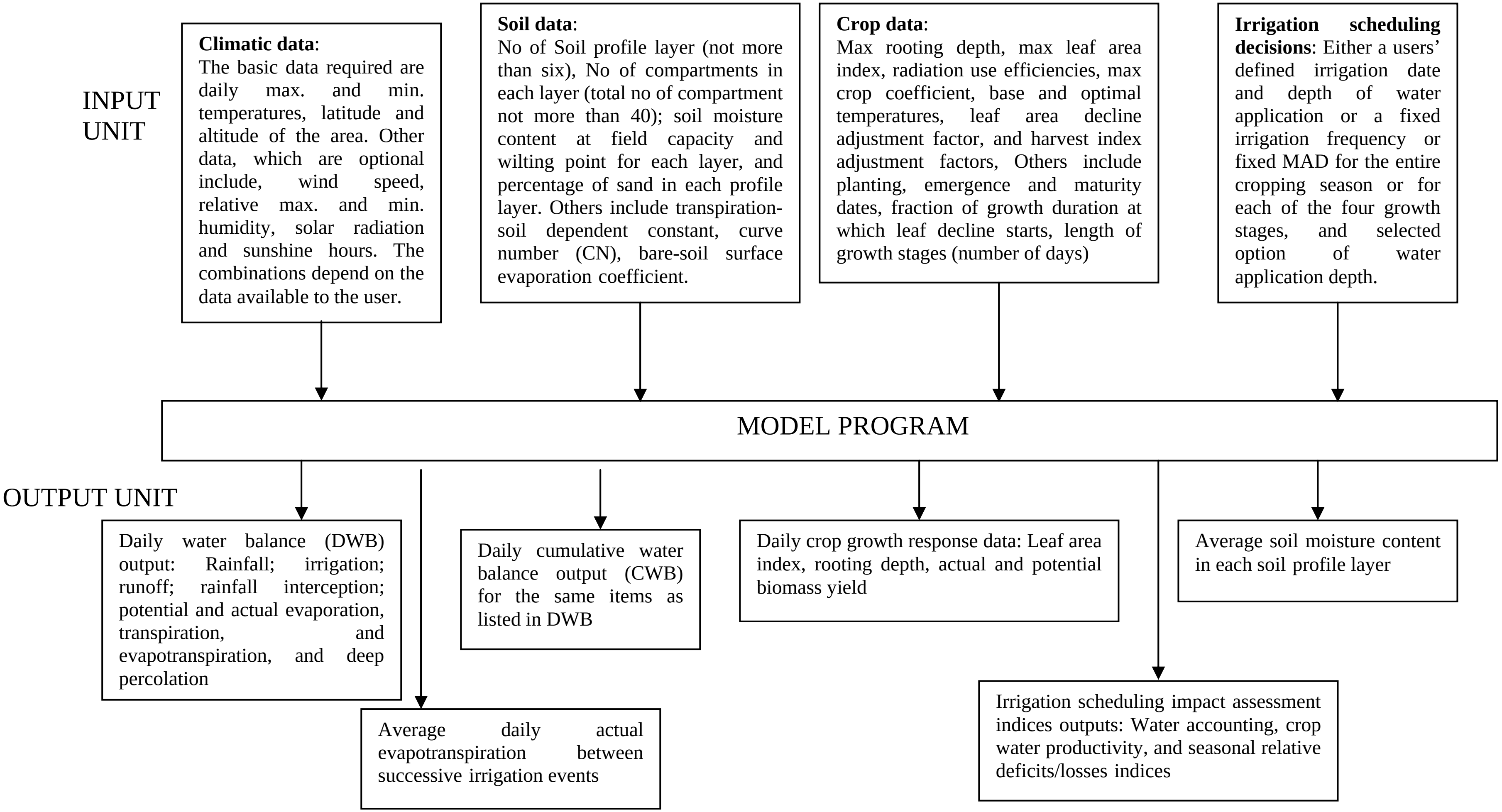
# APPENDIX



**Climatic data**: The basic data required are daily max. and min. temperatures, latitude and altitude of the area. Other data, which are optional include, wind speed, relative max. and min. humidity, solar radiation and sunshine hours. The combinations depend on the data available to the user.

**Soil data**: No of Soil profile layer (not more than six), No of compartments in each layer (total no of compartment not more than 40); soil moisture content at field capacity and wilting point for each layer, and percentage of sand in each profile layer. Others include transpiration-soil dependent constant, curve number (CN), bare-soil surface evaporation coefficient.

**Crop data**: Max rooting depth, max leaf area index, radiation use efficiencies, max crop coefficient, base and optimal temperatures, leaf area decline adjustment factor, and harvest index adjustment factors, Others include planting, emergence and maturity dates, fraction of growth duration at which leaf decline starts, length of growth stages (number of days)

**Irrigation scheduling decisions**: Either a users' defined irrigation date and depth of water application or a fixed irrigation frequency or fixed MAD for the entire cropping season or for each of the four growth stages, and selected option of water application depth.

Daily water balance (DWB) output: Rainfall; irrigation; runoff; rainfall interception; potential and actual evaporation, transpiration, and evapotranspiration, and deep percolation

Average daily actual evapotranspiration between successive irrigation events

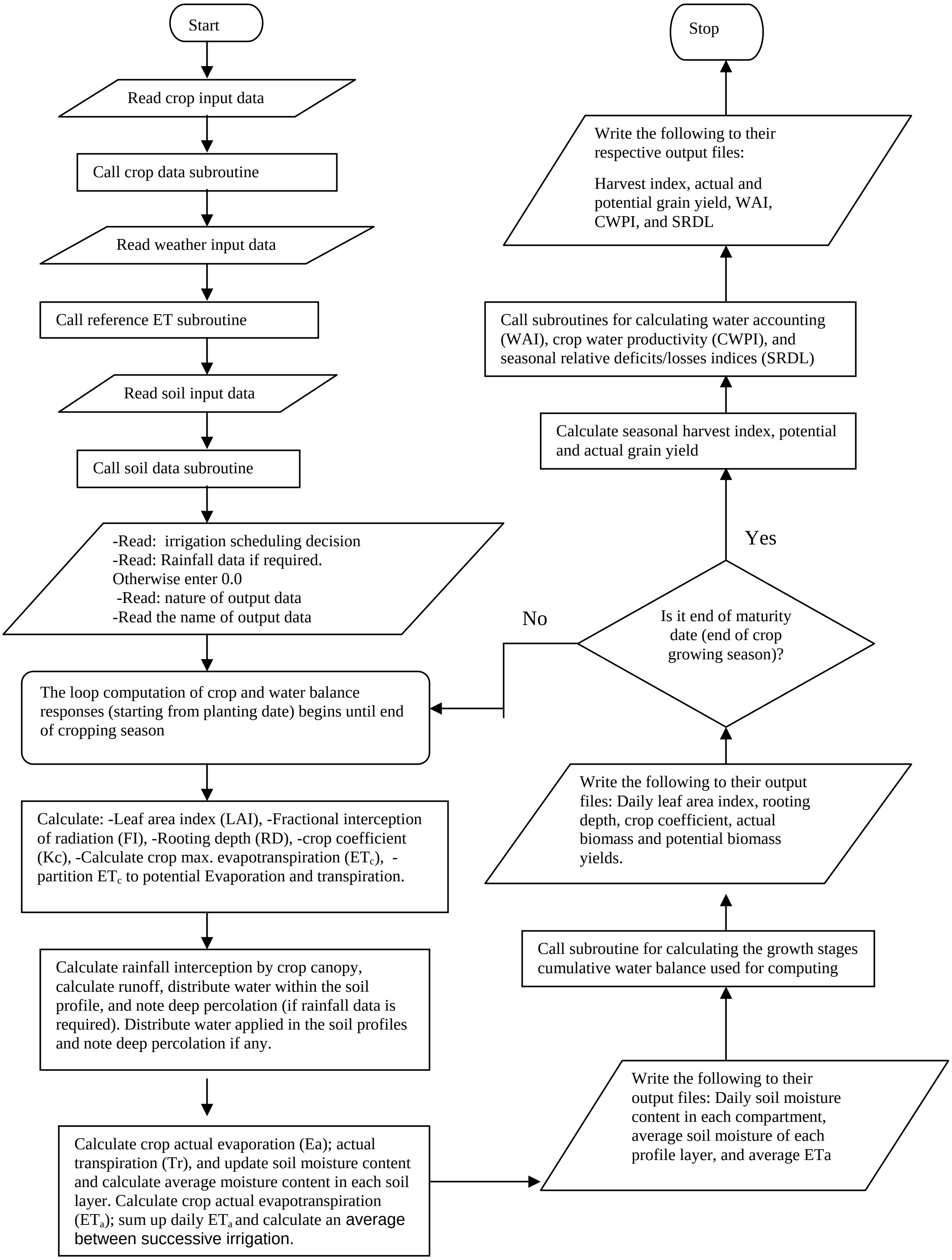
Daily cumulative water balance output (CWB) for the same items as listed in DWB

Daily crop growth response data: Leaf area index, rooting depth, actual and potential biomass yield

Irrigation scheduling impact assessment indices outputs: Water accounting, crop water productivity, and seasonal relative deficits/losses indices

Average soil moisture content in each soil profile layer

Appendix 1: Schematic diagram of the ISIAMod with input and output information



Appendix 2: The flow chart of ISIAMod program