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# Crop water productivity of an irrigated maize crop in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania

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## ABSTRACT

Crop water productivity (CWP) is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production. It is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management. This paper presents CWP quantified from field experimental data. Three fields were cultivated to maize under irrigation during the 2004 dry season in a traditional irrigation scheme in Tanzania. The maize crop was irrigated at eight different seasonal water application depths: 400, 490, 500, 510, 590, 600, 610 and 700 mm, in two of the three fields, and at five water application depths: 400, 590, 600, 610 and 700 mm in the third field. The variation in seasonal water application depth was achieved by skipping the weekly irrigation once after every other irrigation at some pre-defined stages of the crop growth. CWP were computed in terms of crop water use, water applied, and economic returns. The CWP in terms of crop water use was found to range from 0.40 to 0.70 kg/m$^3$ among the treatments in the three fields, while the CWP in terms of water applied varied from 0.40 to 0.55 kg/m$^3$. The amount of irrigation water applied at the different growth stages of the crop and the growth stage response to moisture stress influenced the status of CWP. CWP was maximized by withholding irrigation every other week at vegetative and grain filling and observing weekly irrigation at flowering growth stage. However, the grain yield loss associated with irrigation schedule was about 20–28%. Convincing farmers to accept a trade-off between maximizing CWP at the expense of yield reduction may remain one of the greatest challenges that will face irrigation water management stakeholders.

## 1. Introduction

Water productivity has been defined as the amount of output produced per unit of water involved in the production, or the value added to water in a given circumstance (Molden et al., 1998; Sakthivadivel et al., 1999; Tuong et al., 2000; Bastiaanssen et al., 2003). Water productivity can be defined with respect to the different sectors of production involving water (e.g. crop production, fishery, forestry, domestic and industrial water use). Water productivity with respect to crop production is referred to as crop water productivity (CWP), and is defined as the amount of crop produced per volume of water used. The unit of CWP is kg/m$^3$. CWP can also be defined in monetary terms, expressed in terms of economic return from crop produced per volume of water, with the unit expressed in equivalent of any currency (e.g. \$/m$^3$) (SWMRG, 2003; Kadigi et al., 2004).

The concept of CWP has remained a subject of interest to plant, soil and irrigation scientists for almost 100 years now (Briggs and Shantz, 1916; Richards, 1923; De Wit, 1958; Hanks et al., 1969; Hanks, 1974; Augus et al., 1980; Sinclair et al., 1984; Howell et al., 1990; Musick et al., 1994; Augus and van

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**Table 1 – Examples of definitions of productivity of water by different stakeholders**

| Stakeholder | Useful definition | Scale | Target |
|---|---|---|---|
| Plant physiologists | Dry matter/transpiration | Plant | Productive utilization of light and water resources |
| Agronomist | Yield/evapotranspiration | Field | Higher yields t/ha |
| Larger scale farmer | Yield/water supply | Field | Higher yields t/ha |
| Irrigation engineer | Yield/diverted water | Irrigation scheme | Demand management |
| Water resources planner | $/total water depletion from the basin | River basin | Optimal allocation of water resources |

Source: modified from Bastiaanssen et al. (2003).

Herwaarden, 2001). Another terminology that has frequently been used to express the concept of CWP is water use efficiency (WUE) (e.g. Viets, 1962; French and Schultz, 1984; Zhang and Owie, 1999; Howell, 2001).

CWP is useful for looking at potential increase in crop yield that may result from increased water availability (Burke et al., 1999). It provides a simple means of assessing whether yield is limited by water supply or other factors (Augus and van Herwaarden, 2001). In deficit irrigation scheduling, CWP is a good indicator for assessing the impact of an irrigation scheduling protocol. CWP reveals the unit increment in yield per unit of water use, from which the impact and worth of additional water supply can be assessed. Quantitative information on CWP is therefore necessary for effective planning of irrigation water management strategies in an area.

There are several definitions and expressions used by the different stakeholders in crop-water issues to quantitatively express CWP. For example, Ronald and Marlow (2002) used three efficiency terms to express the concept of CWP. These terms include water use (technical) efficiency, defined as the mass of agricultural produce per unit of water consumed; water use (economic) efficiency, defined as the value of product(s) produced per unit of water volume consumed, and water use (hydraulic) efficiency, defined as the ratio of water actually used by irrigated agriculture to the volume of water supplied.

The draft report of audit of water and irrigation use efficiencies on farms within the Queensland Horticultural Industry (Barraclough & Co, 1999) used the following terms to express the concept of CWP: agronomic water use index (AWUI), defined as the crop yield per volume of water input; crop water use index (CWUI), defined as crop yield per volume of water used by the crop (evapotranspiration) in production; and economic water use index (EWUI), defined as gross revenue per water input. The gross revenue was defined as the product of the kilograms of crop produced and the farm gate price of crop produce per kilogram. Other terms that have been used to express the concept of water productivity include productivity of water use, productivity of water supplied, and economic productivity of water (e.g. Molden (1997) and Molden et al. (1998)). Table 1 summarizes the different stakeholders' definitions and indeed their focus of interest in quantifying water productivity.

The objective of this work was to quantify crop water productivity of a maize crop cultivated under irrigation in the Mkoji sub-catchment of the Great Ruaha River Basin in Tanzania. The paper also examines the prospect and implication of increasing CWP through deficit irrigation scheduling for the maize crop in the study area.

## 2. Materials and methods

### 2.1. *Location of field experiments*

Three field experiments were conducted concurrently in three separate fields in the Tanzanian Ministry of Agriculture Training Institute (MATI) farms located in Igurusi ya Zamani traditional Irrigation Scheme, Mbeya, Tanzania. The irrigation scheme lies at latitude 8.33° South, and longitude 33.53° East, at an altitude of 1100–1120 m above sea level. The source of water for the scheme is the Lunwa River, which is one of the perennial rivers of Mkoji sub-catchment in Rufiji River Basin.

### 2.1.1. *Climate of the study area*

The study area has a unimodal type of rainfall between November and April. The mean annual rainfall in the study area is about 800 mm. Mean daily maximum temperatures range from 28 to 32 °C, while minimum temperatures range from 9.5 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

**Table 2 – Weather data from the Igurusi weather station for the 2004 irrigation season when the field experiments for this study were carried out**

| Month | Maximum air temperature (°C) | Minimum air temperature (°C) | Wind speed (m/s) | Open pan evaporation (mm/day)[a] |
|---|---|---|---|---|
| June | 26.9 | 12.6 | 0.8 | 5.7 |
| July | 28.2 | 10.7 | 1.0 | 6.5 |
| August | 29.5 | 11.5 | 1.1 | 7.1 |
| September | 30.7 | 13.2 | 1.3 | 8.5 |
| October | 32.6 | 13.4 | 1.4 | 8.9 |

[a] Average open pan evaporation for 5 years (1989–1993).

**Table 3 – Experimental treatment description (Fields 1 and 2)**

| Treatment number | Treatment label | Description |
|---|---|---|
| 1 | $TR_{1111}$[a] | Irrigated weekly without skipping irrigation at any crop growth stage (reference treatment) |
| 2 | $TR_{1011}$ | Irrigation was skipped every other week at vegetative stage only. Weekly irrigation was observed at flowering and grain filling growth stages |
| 3 | $TR_{1101}$ | Irrigation was skipped every other week at flowering stage only. Weekly irrigation was observed at vegetative and grain filling growth stages |
| 4 | $TR_{1110}$ | Irrigation was skipped every other week at grain filling stage only. Weekly irrigation was observed at vegetative and flowering growth stages |
| 5 | $TR_{1001}$ | Irrigation was skipped every other week at vegetative and flowering stages. Weekly irrigation was observed only at grain filling growth stage |
| 6 | $TR_{1010}$ | Irrigation was skipped every other week at vegetative and grain filling stages. Weekly irrigation was observed only at vegetative growth stage |
| 7 | $TR_{1100}$ | Irrigation was skipped every other week at flowering and grain filling stages. Weekly irrigation was observed only at vegetative growth stage |
| 8 | $TR_{1000}$ | Irrigation was skipped every other week at vegetative flowering and grain filling stages |

[a] The subscripts represent the growth stages. 1 = weekly irrigation at the growth stage and 0 = irrigation was skipped every other week at the stage.

radiation varies from 7.5 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. Table 2 shows the mean daily weather data from a weather station 4 km from the field experimental site for the 2004 irrigation season.

#### 2.1.2. *Soils of the experimental fields*

The soils of the experimental fields are typical of Usangu plain, which is alluvial clay and clay loam soils (SWMRG, 2003). The water holding capacities of Fields 1, 2 and 3 were 118, 97 and 112 mm/m, respectively. The average soil bulk density of the one metre soil profile depths of Fields 1, 2, and 3 were 1.38, 1.42, 1.38 g/cm$^3$, respectively. Mudstones and gravels were found at about 1 m below the soil surface. These stones hindered the insertion of access tubes and monitoring of soil moisture depth below the 1000 mm depth.

### 2.2. *Experimental treatments description*

Three fields were planted with TMV1–ST maize (*Zea mays* L.) on 24 June 2004. Field 1 was located about 250 m away from Field 2, while the Field 3 was adjacent Field 2, at about 15 m away. The experiments in Fields 1 and 2 consist of eight treatments each, while Field 3 had only five treatments. The treatments description for Fields 1 and 2 is presented in Table 3, while the treatments description for Field 3 is presented in Table 4. Weekly irrigation frequency was maintained in treatments labeled 1 ($TR_{1111}$) in the three fields throughout the crop-growing season. In the other treatments, the weekly irrigation was maintained only at some growth stages, while at one or more growth stages weekly irrigation was skipped after every other irrigation until the targeted growth stage duration elapsed. By skipping the weekly irrigation in a treatment at one or more growth stages, the seasonal water applied for the treatments were varied. The method of varying irrigation regimes by withholding irrigation at some growth stages of the crop was similar to Pandey et al. (2000). The irrigation schedule for Fields 1 and 2 is presented in Table 5a, and the schedule for Field 3 is shown in Table 5b. The scheduling pattern for Field 3 was similar to Fields 1 and 2 except for the number of treatments. The water application depths per weekly irrigation were obtained from a computation of weekly reference evapotranspiration amount using a 5-year open pan evaporation data for the study area using the expression (Allen et al., 1998):

$$ET_o = K_p E_p \quad (1)$$

**Table 4 – Experimental treatment description (Field 3)**

| Treatment number | Treatment label | Description |
|---|---|---|
| 1 | $TR_{1111}$[a] | Irrigated weekly without skipping irrigation at any crop growth stage (reference treatment) |
| 2 | $TR_{1011}$ | Irrigation was skipped every other week at vegetative stage only. Weekly irrigation was observed at flowering and grain filling growth stages |
| 3 | $TR_{1101}$ | Irrigation was skipped every other week at flowering stage only. Weekly irrigation was observed at vegetative and grain filling growth stages |
| 4 | $TR_{1110}$ | Irrigation was skipped every other week at grain filling stage only. Weekly irrigation was observed at vegetative and flowering growth stages |
| 5 | $TR_{1000}$ | Irrigation was skipped every other week at vegetative flowering and grain filling stages |

[a] The subscripts represent the growth stages. 1 = weekly irrigation at the growth stage and 0 = irrigation was skipped every other week at the stage.

**Table 5a – Irrigation schedule for Fields 1 and 2**

| Treatment label | Water application depth per irrigation (mm) | | | | | | | | | | | | | | | | | Total number of irrigation | Total water applied |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Crop establishment | | | Vegetative | | | | | | Flowering | | | | Grain filling | | | | | |
| | 0[a] | 1 | 2[b] | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 ($\mathrm{TR}_{1111}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 40 | 17 | 700 |
| 2 ($\mathrm{TR}_{1011}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 40 | 14 | 590 |
| 3 ($\mathrm{TR}_{1101}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | X | 50 | X | 50 | 50 | 50 | 40 | 15 | 600 |
| 4 ($\mathrm{TR}_{1110}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | 50 | 50 | 50 | 50 | X | 50 | X | 15 | 610 |
| 5 ($\mathrm{TR}_{1001}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | X | 50 | X | 50 | 50 | 50 | 40 | 12 | 490 |
| 6 ($\mathrm{TR}_{1010}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | 50 | 50 | 50 | 50 | X | 50 | X | 13 | 500 |
| 7 ($\mathrm{TR}_{1100}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | X | 50 | X | 50 | X | 50 | X | 13 | 510 |
| 8 ($\mathrm{TR}_{1000}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | X | 50 | X | 50 | X | 50 | X | 10 | 400 |

X = irrigation skipped.

[a] Pre-planting irrigation.

[b] The number of days between successive irrigation was 12 (the interval of irrigation was extended due to conflict of water).

where $ET_o$ is reference evapotranspiration, $K_p$ is class A pan coefficient (taken as 0.7), and $E_p$ is open pan evaporation (class A pan).

The average weekly reference evapotranspiration for each month of the crop-growing season (rounded to tens), were 30, 30, 40, 50, 50 for the months of June, July, August, September and October, respectively. Seasonal water applied for each treatment in Fields 1 and 2 and Field 3 are indicated in Tables 5a and 5b, respectively.

Four distinct phenological growth stages of the crop were considered in this study. These stages include planting to crop establishment, which will be referred to as establishment growth stage in this study (24 days after planting (DfP) with 6–8 leaves); the crop establishment to tasseling initiation stage (24–66 DfP), referred to as the vegetative stage; the tasseling initiation to end of silking stage (66–94 DfP), referred to as flowering stage; and the grain filling to maturity stage (94–126 DfP), referred to as the grain-filling stage in this study. Skipping of regular irrigation events was not observed during the crop establishment stage. This was done purposely to allow the crops to be established before they are allowed to be subjected to moisture stress.

A design irrigation frequency for the three fields was computed based on the crop water requirement for irrigated maize and the soil moisture retention characteristic of the fields. The average design irrigation frequency for the three fields was 10, 6 and 6 days for the vegetative, tasseling to silking, and grain filling to maturity growth stages, respectively. It was therefore expected that by skipping the regular 7-day irrigation event in any treatment, the crops would be subjected to some degree of moisture stress before the next irrigation, due to the evapotranspiration deficit caused by limited soil moisture in the plant root zone.

## 2.3. *Agronomic practices*

The experiment for each field was laid in a randomized complete block design. All the treatments were replicated three times. The experimental blocks were separated by a distance of about 1.5 m, which constitute a walkway and a field-ditch, which carries water to irrigate the plots in the block. The plots sizes were 3.5 by 3.5 m$^2$, and were separated by a distance of about 1.0 m within the blocks. Embankments of 0.30 m high were built around each plot to help retain and prevent runoff/spillover of the water applied. Therefore, each plot constituted a basin. Planting was done on the flat. The crop was planted in rows at plant spacing of 0.75 m between row and 0.30 m between plants. A total of five rows were planted per basin/plot. Three seeds were planted per hole, and

**Table 5b – Irrigation schedule for Field 3**

| Treatment label | Water application depth per irrigation (mm) | | | | | | | | | | | | | | | | | Total number of irrigation | Total water applied |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Crop establishment | | | Vegetative | | | | | | Flowering | | | | Grain filling | | | | | |
| | 0[a] | 1 | 2[b] | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 ($\mathrm{TR}_{1111}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 40 | 17 | 700 |
| 2 ($\mathrm{TR}_{1011}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 40 | 14 | 590 |
| 3 ($\mathrm{TR}_{1101}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | X | 50 | X | 50 | 50 | 50 | 40 | 15 | 600 |
| 4 ($\mathrm{TR}_{1110}$) | 30 | 30 | 30 | 30 | 30 | 40 | 40 | 40 | 40 | 50 | 50 | 50 | 50 | 50 | X | 50 | X | 15 | 610 |
| 5 ($\mathrm{TR}_{1001}$) | 30 | 30 | 30 | 30 | X | 40 | X | 40 | X | 50 | X | 50 | X | 50 | X | 50 | X | 10 | 400 |

Treatment 5 is similar to treatment 8 in Fields 1 and 2. X = irrigation skipped.

[a] Pre-planting irrigation.

[b] The number of days between successive irrigation was 12 (the interval of irrigation was extended due to conflict of water).

3 weeks after germination, the plants in each basin were thinned to one per stand, to a population of 60 plants per plot, and a projection of about 44,444 plants/ha.

Di-ammonium phosphate (DAP) fertilizer (N:P:K 18:46:0) was applied at the rate of 60 kg P/ha at planting by placing the fertilizer 6–8 cm away from the hole where the seeds were placed. Top-dressing was carried out at 5 weeks after planting using urea fertilizer. The total Nitrogen applied from the two fertilizer applications was 120 kg N/ha. Weeding was carried out two times in Fields 1 and 3, and four times in Field 2, before harvesting. Weed proliferation was high in Field 2. There was no incident of pest and diseases in any of the fields. The crop was considered physiologically matured at about 125 days from planting, but was allowed to dry on the field before harvesting. The harvested maize cobs were threshed and weighed to obtain the grain weight. The grain moisture content at threshing was determined in the laboratory and was found to be about 13%.

### 2.4. *Measurement of water application depths*

The method of irrigation was surface. An average discharge of 4 l/s was diverted from a tertiary canal into each of the experimental fields to irrigate the crop. The discharge runs in the field ditches that were built to carry water into the field plots. An entrance for water into each plot was constructed with brick and it floor was lined with mortar to avoid erosion. In order to measure the depth of water applied to each plot, a graduated staff gauge was placed at the each entrance. Each staff gauge was calibrated using a cutthroat flume. With the aid of a calculator and a stopwatch, the discharge into each plot/basin and the time required to apply the desired depth of water was immediately calculated as soon as water was introduced into the basin. Water was allowed into the basin for the time calculated. Sheet metal plates were used to cut off the flow into the plots at the end of the calculated time and to close the entrance to stop water from entering the plots. The metal sheets were also used to close the entrances of the plots when the irrigation was skipped.

### 2.5. *Soil moisture measurement*

Soil moisture content was monitored throughout the crop-growing season using a ML1 Theta Probe (Delta-T Devices, Cambridge), which measures volumetric soil moisture content expressed in $m^3/m^3$. Soil moisture content measurements were carried out twice a week in all the plots in the three fields. Moisture measurement was done at 2 days after an irrigation event and on the day of the next irrigation (7th day after irrigation). When irrigation was skipped in any treatment, soil moisture content was measured 2, 7 and 9 days after irrigation, and just before the next irrigation event (i.e. the 14th day). It was assumed that soil moisture content of the field would be at field capacity and deep percolation will be negligible 2 days after irrigation since the fields were fairly drained soils (Pandey et al., 2000). Soil moisture measurements were carried out at depths of about 8, 25, 55, and 80 cm below the soil surface. The measurements taken at these depths were use to represent soil profile depths of 0–15, 15–40, 40–70, and 70–100 cm, respectively. Three pieces of 7.6 cm diameter PVC pipes were installed to the depths of 25, 55 and 80 cm, respectively, in each plot to provide access for inserting the theta probe into the soil. In order to measure the moisture content of the 0–15 cm depth, a hand hoe was used to open up the soil surface to the depth of about 6–8 cm before inserting the probe into the soil.

### 2.6. *Calculation of crop water use (crop actual evapotranspiration)*

The average crop consumptive use (actual crop evapotranspiration) (mm/day) between two successive soil moisture content sampling was calculated using the soil moisture depletion studies method (Michael, 1978). The average daily crop consumptive use was expressed as:

$$\mathrm{AWU} = \frac{\sum_{i=1}^{n}(\mathrm{VMC}_{1i} - \mathrm{VMC}_{2i})D_i}{t} \tag{2}$$

where AWU = crop consumptive use for successive soil moisture content sampling periods (mm/day), $\mathrm{VMC}_{1i}$ = volumetric moisture content ($m^3/m^3$) at the time of first sampling in the $i$th soil layer, $\mathrm{VMC}_{2i}$ = volumetric moisture content ($m^3/m^3$) at the time of second sampling in the $i$th layer, $D_i$ = depth of $i$th layer (mm), $n$ = number of soil layers sampled in the root zone depth $D$ and $t$ = number of days between successive soil moisture content sampling.

The crop consumptive use for a week was therefore the product of the daily crop consumptive use from successive soil moisture content sampling and the number of days in the week. The total crop consumptive use for a growth stage and for the entire crop-growing season (seasonal evapotranspiration) was therefore the summation of the weekly crop water use for the growth stage and the entire crop-growing season, respectively.

### 2.7. *Computation of crop water productivity*

Crop water productivity was calculated as:

1. Crop water productivity in terms of seasonal crop consumptive use (SWU) was obtained as:

$$\mathrm{CWP}_{(\text{consumptive use})} = \frac{\text{Crop yield (kg)}}{\text{SWU (m}^3\text{)}} \tag{3}$$

2. Crop water productivity in terms of water applied (SWA) to the fields was obtained as:

$$\mathrm{CWP}_{(\text{water applied})} = \frac{\text{Crop yield (kg)}}{\text{SWA (m}^3\text{)}} \tag{4}$$

3. Crop water productivity expressed in economic term was obtained as:

$$\mathrm{CWP}_{(\text{economic})} = \frac{p \times \text{Crop yield}}{\text{SWA (m}^3\text{)}} \tag{5}$$

where $p$ = price of maize grain (price/kg crop yield). The price of maize grain in the study area during the 2004 irrigated season was equivalent to about \$0.06/kg.

**Table 6 – Grain yield, crop consumptive use and depth of water applied in the growth stages (Field 1)**

| Treatment | Grain yield (t/ha) | Crop water use (mm) | Water applied in each growth stage (mm) | | | | Seasonal water applied (mm) (1 + 2 + 3 + 4) |
|---|---|---|---|---|---|---|---|
| | | | Stage 1 | Stage 2 | Stage 3 | Stage 4 | |
| 1 ($TR_{1111}$) | 3.78 a | 541.40 a | 90 | 220 | 200 | 190 | 700 |
| 2 ($TR_{1011}$) | 3.06 b | 487.95 c | 90 | 110 | 200 | 190 | 590 |
| 3 ($TR_{1101}$) | 2.77 c | 503.12 b | 90 | 220 | 100 | 190 | 600 |
| 4 ($TR_{1110}$) | 2.81 c | 504.58 b | 90 | 220 | 200 | 100 | 610 |
| 5 ($TR_{1001}$) | 2.25 d | 443.44 d | 90 | 110 | 100 | 190 | 490 |
| 6 ($TR_{1010}$) | 2.73 c | 446.95 d | 90 | 110 | 200 | 100 | 500 |
| 7 ($TR_{1100}$) | 2.25 d | 451.16 d | 90 | 220 | 100 | 100 | 510 |
| 8 ($TR_{1000}$) | 1.64 e | 385.48 e | 90 | 110 | 100 | 100 | 400 |

## 3. Results and discussion

### 3.1. Crop yield response to water applied

The grain yield, seasonal crop water use and seasonal water applied of Fields 1, 2, and 3 are presented in Tables 6–8, respectively. The highest grain yields and crop water use in the three fields were recorded in treatments 1, which received 700 mm of water in the season. The lowest grain yields and crop water use were recorded in the treatments 8 in Fields1 and 2, and treatment 5 in Field 3, which received only 400 mm of water in the season. An analysis of variance test for each field showed that the mean differences in grain yields among the treatments were highly significant ($P < 0.01$). The mean differences in crop water use among the treatments in each field were also highly significant.

Grain yield from the experiments were quite adequate as they compared well with world's average grain yield of maize given as 2000–4500 kg/ha (IITA, 2005). The grain yields were above the average grain yield of maize in sub-Saharan Africa but were far below the average for USA. Average grain yield of maize in sub-Saharan Africa and the USA were given as 1316 and 8600 kg/ha, respectively (IITA, 2005). However, the grain yields from the experiments even from the well-irrigated treatments were lower than the potential yield of the TMV1 maize variety, being 4.5–5.5 t/ha at optimum altitude of 600–900 m above mean sea level (Dr. Moshi, 2005. Personal communication). The reason for the lower yield may be attributed to fact that the altitude of the experimental location was higher than the altitude for best performance of the maize variety. The altitude of the experimental location was 1100–1200 m above mean sea level.

A comparison of the mean grain yields of the treatments where irrigation was skipped at one growth stage only (treatments 2 ($TR_{1011}$), 3 ($TR_{1101}$), and 4 ($TR_{1110}$) in Fields 1 and 2) and those where irrigation was skipped at two stages (treatments 5 ($TR_{1001}$), 6 ($TR_{1010}$), and 7 ($TR_{1100}$)) showed that the crop yield response was very much dependent on the

**Table 7 – Grain yield, crop consumptive use and depth of water applied in the growth stages (Field 2, located 250 m away from Field 1)**

| Treatment | Grain yield (t/ha) | Crop water use (mm) | Water applied in each growth stage (mm) | | | | Seasonal water applied (mm) (1 + 2 + 3 + 4) |
|---|---|---|---|---|---|---|---|
| | | | Stage 1 | Stage 2 | Stage 3 | Stage 4 | |
| 1 ($TR_{1111}$) | 3.09 a | 548.73 a | 90 | 220 | 200 | 190 | 700 |
| 2 ($TR_{1011}$) | 2.94 a | 494.19 b | 90 | 110 | 200 | 190 | 590 |
| 3 ($TR_{1101}$) | 2.20 c | 505.68 b | 90 | 220 | 100 | 190 | 600 |
| 4 ($TR_{1110}$) | 2.46 b | 496.14 b | 90 | 220 | 200 | 100 | 610 |
| 5 ($TR_{1001}$) | 2.12 c | 449.49 c | 90 | 110 | 100 | 190 | 490 |
| 6 ($TR_{1010}$) | 2.50 b | 452.87 c | 90 | 110 | 200 | 100 | 500 |
| 7 ($TR_{1100}$) | 2.25 c | 449.84 c | 90 | 220 | 100 | 100 | 510 |
| 8 ($TR_{1000}$) | 1.64 d | 395.78 d | 90 | 110 | 100 | 100 | 400 |

**Table 8 – Grain yield, crop consumptive use and depth of water applied in the growth stages (Field 3, located 15 m adjacent Field 2)**

| Treatment | Grain yield (t/ha) | Crop water use (mm) | Water applied in each growth stage (mm) | | | | Seasonal water applied (mm) (1 + 2 + 3 + 4) |
|---|---|---|---|---|---|---|---|
| | | | Stage 1 | Stage 2 | Stage 3 | Stage 4 | |
| 1 ($TR_{1111}$) | 3.60 a | 537.15 a | 90 | 220 | 200 | 190 | 700 |
| 2 ($TR_{1011}$) | 3.02 b | 484.27 b | 90 | 110 | 200 | 190 | 590 |
| 3 ($TR_{1101}$) | 2.79 c | 471.60 c | 90 | 220 | 100 | 190 | 600 |
| 4 ($TR_{1110}$) | 2.71 c | 495.15 b | 90 | 220 | 200 | 100 | 610 |
| 5 ($TR_{1001}$) | 1.58 d | 395.30 d | 90 | 110 | 100 | 100 | 400 |

amount of water applied in a growth stages rather than the overall seasonal water applied. For example, in Field 1 (Table 6), the depth of water applied at growth stages 2 (the vegetative stage) and 4 (grain filling to maturity stage) in treatment 6 were about half the amount applied at the same growth stages in treatment 3. And in stage 3 (the tasseling to silking stage) about twice the amount of water applied in treatment 3 was applied in treatment 6. However, grain yield in treatment 6 was not significantly different from treatment 3. The same amount of water was applied at growth stages 3 and 4 in both treatments 4 and 6, while at growth stage 2, the depth of water applied in treatment 6 was 50% less than what was applied in treatment 4. Grain yield in treatments 4 and 6 were also not significantly different, even though the seasonal water applied in treatment 6 was about 18% less than treatment 3 and 4. Similar trends were noticed in Field 2 where the grain yields of treatments 6 and 7 were also not significantly different from treatments 4 and 3, respectively, while seasonal water applied in treatments 6 and 7 were about 18% less than treatments 4 and 3, respectively.

A comparison of grain yields of treatments 2, 3, and 4 where regular irrigation was skipped every other week at single growth stage showed that yields of treatment 2 were significantly different from treatments 3 and 4 across the three fields, even though the seasonal water applied in field 2 was about 5% less than treatments 3 and 4. Water applied at the vegetative growth stage in treatment 2 was 50% less than what was applied in treatment 3 and 4. However, water applied at growth stages 3 and 4 in treatment 2 were about twice the amount applied in treatments 3 and 4, respectively. The higher yield response from treatment 2 compared to treatments 3 and 4 was due to adequate water applied at the tasseling and grain filling growth stages which were more critical in terms of water requirement. Adequate water applied at tasseling stage was also responsible for better yields in treatment 6 compared to treatments 5 and 7 where regular irrigation events were skipped in two growth stages. These results suggest that with deficit water application at the vegetative growth stage, and adequate water applied at the other growth stages of the maize crop, grain yield can be maximized. More so, adequate water applied at tasseling to silking growth stages of the maize crop and a deficit in water applied at the vegetative and grain filling growth stages would minimize grain yield losses of the maize crop.

### 3.2. *Relative yield decrease–relative evapotranspiration deficit relationship*

The relationship between relative yield decrease and relative evapotranspiration deficit (for the data of the three experimental fields combined) is shown in Fig. 1. The regression equation for the relationship was obtained as:

$$\left(1-\frac{\mathrm{Y_a}}{\mathrm{Y_m}}\right)=1.9\times\left(1-\frac{\mathrm{ET_a}}{\mathrm{ET_m}}\right) \tag{6}$$

The coefficient of determination ($r^2$) was 0.76. Where $\mathrm{Y_m}$ = yield obtained from treatment which received weekly irrigation throughout the crop-growing seasons; $\mathrm{Y_a}$ = yield from the other treatments in which irrigation was skipped every other week at one or more growth stages in the crop growing season; $\mathrm{ET_m}$ = seasonal evapotranspiration from treatment which received weekly irrigation throughout the crop-growing season; $\mathrm{ET_a}$ = seasonal evapotranspiration from the other treatments in which irrigation was skipped every other week at one or more growth stages in the crop growing season.

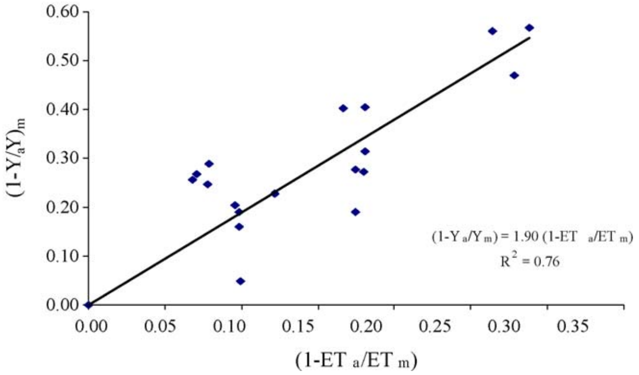

**Fig. 1 – Relationship between relative yield decrease ($1-\mathrm{Y_a}/\mathrm{Y_m}$) and relative evapotranspiration deficit ($1-\mathrm{ET_a}/\mathrm{ET_m}$) for the three experiments data combined.**

Eq. (6) is the well-known water production function of Doorenbos and Kassam (1979). Doorenbos and Kassam (1979) referred to the slope of the expression as the crop yield response factor ($K_y$). The $K_y$ value obtained in this study ($K_y$ = 1.90) was higher than the 1.25 and 1.33 values for maize in FAO Irrigation and Drainage paper no. 33 and the International Atomic Energy Agency coordinated research programme (IAEA-CRP) (Moutonnet, 2002), respectively. $K_y$ values greater than unity is an indication of severe moisture stresses or low resistance to moisture stress. It implies that the rate of relative yield decrease resulting from moisture stress is proportionally higher than the relative evapotranspiration deficit. The high value for $K_y$ obtained in this study is an indication that the moisture stresses imposed on the crop due to withholding irrigation every other week at in multiple growth stages was severe. This fact can be seen clearly from the differences in yield between the weekly irrigated treatments and those in which irrigation was skipped on two or more growth stages.

### 3.3. *Crop water productivity*

The computed $\mathrm{CWP_{(consumptive\ use)}}$, $\mathrm{CWP_{(water\ applied)}}$ and $\mathrm{CWP_{(economic)}}$ for Fields 1, 2 and 3 are presented in Tables 9–11, respectively. $\mathrm{CWP_{(consumptive\ use)}}$ for the three fields varied from 0.40 to 0.70 kg/m$^3$, while $\mathrm{CWP_{(water\ applied)}}$ varied from 0.40 to 0.55 kg/m$^3$. In Fields 1 and 3, treatments 1 which received a 700 mm depth of water in the cropping season recorded the highest $\mathrm{CWP_{(consumptive\ use)}}$, being 0.70 kg/m$^3$ in Field 1 and 0.67 kg/m$^3$ in Field 3, while the least values of $\mathrm{CWP_{(consumptive\ use)}}$ were recorded in treatments 8 and 5 in the respective fields. These treatments received a seasonal water depth of 400 mm. However, treatment 2 in Field 2, which received a seasonal water depth of 590 mm, recorded the highest value of $\mathrm{CWP_{(consumptive\ use)}}$ being 0.59 kg/m$^3$. The results imply that 70 kg/ha of maize was produced per 100 m$^3$ of water used by the crop in treatment 1 in Field 1 while 67 and 59 kg/ha of maize was produced per 100 m$^3$ of water used by the crop in treatment 1 in Fields 2 and 3, respectively.

**Table 9 – Crop water productivity (Field 1)**

| Treatment | $CWP_{(water\ use)}$ (kg/m$^3$) | $CWP_{(water\ applied)}$ (kg/m$^3$) | $CWP_{(economic)}$ (\$/m$^3$) |
|---|---|---|---|
| 1 ($TR_{1111}$) | 0.70 | 0.54 | 0.032 |
| 2 ($TR_{1011}$) | 0.63 | 0.52 | 0.031 |
| 3 ($TR_{1101}$) | 0.55 | 0.46 | 0.028 |
| 4 ($TR_{1110}$) | 0.56 | 0.46 | 0.028 |
| 5 ($TR_{1001}$) | 0.51 | 0.46 | 0.028 |
| 6 ($TR_{1010}$) | 0.61 | 0.55 | 0.033 |
| 7 ($TR_{1100}$) | 0.50 | 0.44 | 0.027 |
| 8 ($TR_{1000}$) | 0.42 | 0.41 | 0.025 |

A comparison of the $CWP_{(consumptive\ use)}$ of the treatments where regular weekly irrigation was skipped in any one growth stage only (treatments 2, 3, 4) showed that maize production per unit of water used in treatment 2 was about 13% and 11% higher than treatments 3 and 4, respectively, in Field 1. In Field 2, the maize produced per unit of water in treatment 2 was about 25% and 15% higher than treatments 3 and 4, respectively. The results imply that treatment 2 had a better water utilization efficiency than treatments 3 and 4. Treatment 6 in both Fields 1 and 2 was also found to have better water utilization efficiency among the treatments where irrigation was skipped in two crop growth stages. Maize production per unit of water used in treatment 6 was about 16% and 18% higher than treatments 5 and 7, respectively, in Field 1, and about 15% and 9% higher than treatments 5 and 7, respectively, in Field 2. $CWP_{(consumptive\ use)}$ of treatment 6 in both fields were also noticed to be higher than those of treatments 3 and 4. Better water utilization efficiency in treatment 6 may be associated with adequate water applied during the tasseling to silking growth stage. These results imply that the crop growth stage at which a deficit irrigation measures are imposed on the crop will determine the status of CWP.

Crop water productivity expressed in terms of water applied ($CWP_{(water\ applied)}$) varied from 0.40 kg/m$^3$ to 0.55 kg/m$^3$. In Fields 1 and 2, the highest values of $CWP_{(water\ applied)}$ were recorded in treatment 6 which received a seasonal water depth of 500 mm. The least values of $CWP_{(water\ applied)}$ were recorded in the treatments which received seasonal water depth of 400 mm. $CWP_{(water\ applied)}$ is an indicator of how much the total water applied to the field was efficiently harness for production benefit. This means that in Field 1, 55 kg/ha of maize was produced from every 100 m$^3$ applied to grow the crop in treatment 6, and in Field 2, 50 kg/ha of maize was also produced from 100 m$^3$ of water applied in treatment 6, while 54, 44, and 51 kg/ha of grain was produced from 100 m$^3$ of water applied in treatments 1 in Fields 1, 2, and 3, respectively. $CWP_{(water\ applied)}$ were noticed to be about 2% and 12% higher in treatments 6 than in treatments 1 for Fields 1 and 2, respectively. This implies that treatment 6 had better yield-water supply conversion efficiency. In other words, although treatment 1 had a higher $CWP(_{consumptive\ use)}$ than treatment 6, the efficiency of harnessing the total water supply for production benefit was lower than treatment 6. This is so because regular water supply might have left the soil surface wet thereby aiding evaporation losses. Water removed from the soil through evaporation does not contribute to crop production. The economic crop water productivity varied from a least value of 0.024 \$/m$^3$ in the treatments which received the lowest seasonal water applied to grow the crop to a highest value of 0.033 \$/m$^3$ in treatment 6 in Field 1. The trend of the economic water productivity has similar trend with the $CWP_{(water\ applied)}$.

**Table 10 – Crop water productivity (Field 2)**

| Treatment | $CWP_{(water\ use)}$ (kg/m$^3$) | $CWP_{(water\ applied)}$ (kg/m$^3$) | $CWP_{(economic)}$ (\$/m$^3$) |
|---|---|---|---|
| 1 ($TR_{1111}$) | 0.56 | 0.44 | 0.027 |
| 2 ($TR_{1011}$) | 0.59 | 0.50 | 0.030 |
| 3 ($TR_{1101}$) | 0.44 | 0.37 | 0.022 |
| 4 ($TR_{1110}$) | 0.50 | 0.40 | 0.024 |
| 5 ($TR_{1001}$) | 0.47 | 0.43 | 0.026 |
| 6 ($TR_{1010}$) | 0.55 | 0.50 | 0.030 |
| 7 ($TR_{1100}$) | 0.50 | 0.44 | 0.027 |
| 8 ($TR_{1000}$) | 0.41 | 0.41 | 0.025 |

**Table 11 – Crop water productivity (Field 3)**

| Treatment | $CWP_{(water\ use)}$ (kg/m$^3$) | $CWP_{(water\ applied)}$ (kg/m$^3$) | $CWP_{(economic)}$ (\$/m$^3$) |
|---|---|---|---|
| 1 ($TR_{1111}$) | 0.67 | 0.51 | 0.031 |
| 2 ($TR_{1011}$) | 0.62 | 0.51 | 0.031 |
| 3 ($TR_{1101}$) | 0.59 | 0.46 | 0.028 |
| 4 ($TR_{1110}$) | 0.55 | 0.44 | 0.027 |
| 5 ($TR_{1001}$) | 0.40 | 0.40 | 0.024 |

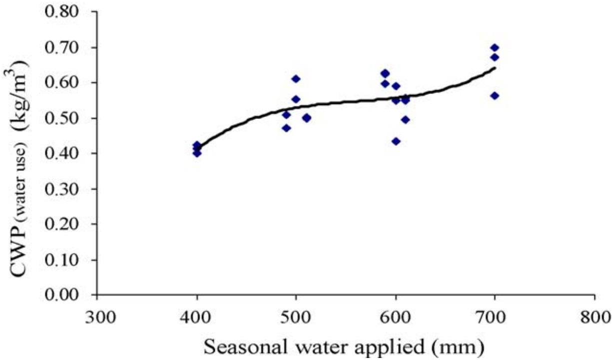

**Fig. 2 – Relationship between seasonal irrigation water applied and crop water productivity in terms of crop water use. (Due to overlapping of data points, only 18 points seems to be shown on the graph.)**

The ranges of crop water productivity from the three fields fall within the range of 0.3 and 2.7 kg/m$^3$ reported in literature for maize crop around the world (Bastiaannssen, 2000, as cited by Bastiaanssen et al., 2003). However, the highest values obtained fell below the crop water productivity range for maize in China and the developed world, being 1.2–1.5 kg/m$^3$ and 2.0–2.5 kg/m$^3$, respectively (Zhang, 2002). It must however be noted that crop water productivity values are influenced by crop variety and water management practices (Van Dam and Malik, 2003). The maize variety planted in this experiment was a composite which is not a high yielding variety, especially when compared with hybrids. This may have been responsible for the low CWP values compared to what is obtainable in China and other developed countries. Moreover, the method of irrigation used in this study was surface irrigation which is prone to lower water application efficiency compared to sprinkler systems common in developed world. There is therefore a greater tendency for lower CWP in terms of water applied.

### 3.4. *Relationship between seasonal irrigation water applied and crop water productivity in terms of crop consumptive use*

Fig. 2 shows the relationship between seasonal water applied and crop water productivity in terms of crop consumptive use (for the data of the three experimental fields combined). Fig. 2 shows four groups of data point clusters on the graph. The first group of cluster at the extreme right of the graph is the CWP of treatments which received weekly irrigation throughout the crop growing season. The second group of cluster is the CWP of treatments which received bi-weekly (14-day interval) irrigation at any one of the vegetative, flowering and grain filling growth stages of the crop. The third group of cluster is the CWP of treatments where irrigation was skipped in any two growth stages, while the fourth cluster was for treatments which were irrigated bi-weekly throughout the crop growing season except at crop establishment growth stage. The data points above the graph line in the second cluster group were the CWP for treatments where irrigation was skipped at vegetative stage while the data points below the line were CWP for treatments where irrigation was skipped at flowering growth stage. The flowering growth stage in this study was from tasseling formation to silking. The data points above the line in the third cluster group were CWP of treatments where irrigation was skipped at vegetative and grain filling stages but were irrigated at weekly interval at flowering stage.

The results imply that reducing the amount of water applied to the maize field by withholding irrigation every other week at some crop growth stages may not necessarily increase CWP. The amount of water reduced, the number of crop growth stages and the type of growth stages at which such water conservation measure is carried will determine the status of CWP. This results support the remark of Zwart and Bastiaanssen (2004) that beside the total amount of irrigation water applied, the timing of irrigation is important in increasing CWP; and that water stress during different growth stages affects CWP differently. Although in all the experiments in this study, CWP of the treatments where irrigation was withheld every other week in any growth stage fell below what was obtainable when the crop were irrigated on weekly basis. It appears, perhaps that CWP could be maximized by withholding irrigation every other week at vegetative and grain filling and observing weekly irrigation at flowering growth stage. However, the grain yield loss associated with such schedule was about 20–28%. This may not be desirable by farmers whose aim is to maximize land productivity and economic profitability. Convincing farmers to adopt the less irrigation-maximizing CWP policies therefore will remain one of the greatest challenge that faces stakeholders in irrigation water management.

## 4. Conclusion

Crop water productivity (CWP) in terms of crop water use, water applied and economic returns were computed for irrigated maize crop based on field experimental data. The $\mathrm{CWP}_{\text{(water use)}}$ was found to vary from 0.40 to 0.70 kg/m$^3$ while the $\mathrm{CWP}_{\text{(water applied)}}$ varied from 0.40 to 0.55 kg/m$^3$. The CWP expressed in economic terms also varied from 0.025 to 0.033 \$/m$^3$. The status of crop water productivity (either maximized or reduced), was dictated by the amount of water applied, the growth stages at which irrigation was reduced, and the frequency of withholding irrigation. An attempt to maximize CWP by withholding irrigation in multiple growth stages resulted in significant reduction in crop yield. Convincing farmers to accept a tradeoff between maximizing CWP at the expense of yield reduction may remain one of the greatest challenges that will face irrigation water management stakeholders.

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