Using a field water balance methodology to assess water production functions for irrigated sugarcane (Saccharum Officinarum L.) in semi-arid environment

Sachin Krishanrao Dingre[1]

[1]Mahatma Phule Krishi Vidyapeeth, Rahuri, India

November 23, 2022

Abstract

The water production function (Ky) defines the quantitative response of the water deficit to overall yield during a given phenological stage and is a key parameter in deficit irrigation planning in water-scarce scenarios A three-year field trials were carried out on clay loam soil of semiarid India in complete randomized blocks with 27 treatments and 2 replicates. Treatments consisted of applying irrigation depths equivalents to 100%, 70% and 40% replenishments of the soil water from the root zone at development, mid-season and end stages of sugarcane. Each treatment was defined to investigate effect of specified water depth on specified phenological stage independently. The actual evapotranspiration (ETa) was determined by the field water balance of the root zone while the Ky were calculated according to the FAO-33 report methodology. In particular, during the mid-season and development stages, the referred yield decreases have been shown to be responsive to water deficits. Seasonal Ky values ranged from 1.05 to 1.18 over 3 seasons with an average value of 1.11 showing sugarcane intolerant to water deficit (Ky $>$ 1). Based on the phenological stage ETa, Ky values for development, mid-season and end stages were 0.31, 0.76 and 0.07, respectively. Ky values calculated for development and mid-season stage in this research was different than FAO-33. It could be concluded that during mid-season, water deficit must be avoided; 30 % and 60 % water deficit are appropriate if applied respectively in the in development and end stages.

Hosted file

essoar.10507699.1.docx available at https://authorea.com/users/544577/articles/601748-using-a-field-water-balance-methodology-to-assess-water-production-functions-for-irrigated-sugarcane-saccharum-officinarum-l-in-semi-arid-environment

Using a field water balance methodology to assess water production functions for irrigated sugarcane (*Saccharum Officinarum L.*) in semi-arid environment

S.K. Dingre *and S.D. Gorantiwar

Mahatma Phule Krishi Vidyapeeth, Rahuri - 413 722, Dist. Ahmednagar, Maharashtra, (INDIA)

**Corresponding author email:* `sachindingre@rediffmail.com`

Abstract

The water production function (Ky) defines the quantitative response of the water deficit to overall yield during a given phenological stage and is a key parameter in deficit irrigation planning in water-scarce scenarios A three-year field trials were carried out on clay loam soil of semiarid India in complete randomized blocks with 27 treatments and 2 replicates. Treatments consisted of applying irrigation depths equivalents to 100%, 70% and 40% replenishments of the soil water from the root zone at development, mid-season and end stages of sugarcane. Each treatment was defined to investigate effect of specified water depth on specified phenological stage independently. The actual evapotranspiration (ETa) was determined by the field water balance of the root zone while the Ky were calculated according to the FAO-33 report methodology.

In particular, during the mid-season and development stages, the referred yield decreases have been shown to be responsive to water deficits. Seasonal Ky values ranged from 1.05 to 1.18 over 3 seasons with an average value of 1.11 showing sugarcane intolerant to water deficit (Ky > 1). Based on the phenological stage ETa, Ky values for development, mid-season and end stages were 0.31, 0.76 and 0.07, respectively. Ky values calculated for development and mid-season stage in this research was different than FAO-33. It could be concluded that during mid-season, water deficit must be avoided; 30 % and 60 % water deficit are appropriate if applied respectively in the in development and end stages.

Keywords: Actual cropevapotranspiration (ETa), Phenological stage, Irrigation depths, Soil water replenishment, Reduced yields, Water production fucntion (Ky)

1. Introduction

The most important sugar crop in India is sugarcane (Saccharum species hybrid L.). India is the world's second-largest sugar producer, accounting for 15% of global demand. (CACP, 2019). The state of Maharashtra is a major contributor to sugar production in the western part of India, contributing to over 70 percent of India's total sugar production. Being in the semi-arid zone and having a large number of large dams, the region has a natural advantage in sugarcane cultivation (Pawar *et al.*,2014).Sugarcane in this region is the most lucrative crop grown by farmers and has brought about desirable changes in socio-economic conditions in various aspects (Hirwe and Jadhav, 2009).In Maharashtra, however, most sugar cane cultivation falls within a low rainfall region and supplemental irrigation is needed to meet at least 70% of the crop's water requirement. Periodic droughts in the area and increased demand for water from urban and industrial users are reducing the amount of water available for agriculture (Pawar *et al.,* 2013). During the long growth cycle of sugarcane crops, water is not always available in the desired quantity, resulting in a significant loss of productivity. Moreover, flood irrigation is often used to irrigate sugar cane in canal control areas that provide 2-3 times the required excess water (Kumar *et al.,* 2005; Shrivastava *et al.,*2011). Excess water uses by flood irrigation, which is reflected in the continuous decrease in productivity of sugar cane in recent decades despite the production of many high yielding varieties (Garkar *et al.,* 2011). It is therefore increasingly important for water to be used carefully, so that less sugarcane area is used, and thus requiring less sugarcane water volume, which is possible by deficit irrigation. By using deficit irrigation based on a reasonable knowledge of the water usage and yield of sugarcane plants in these areas, considerable water savings can be achieved (Hargreaves and Samani, 1984; Dingre and Gorantiwar, 2020).

Sugarcane is a long-term crop that requires a lot of water, so the yield response to irrigation deficit in different growth periods needs to be understood (Inman-Bamber, 2004). When a water deficit occurs during a specific part of a crop's total growing period, the yield reaction to the water deficit can vary dramatically based on how sensitive the crop is during that growing period (English Raja, 1996; Carr and Knox, 2011, Ethan *et al.* 2016). The rate of actual evapotranspiration (ETa) can be quantified by the water deficit in the plant compared to the rate of maximum evapotranspiration (ETm). When crop water uses are entirely met by available water supply then ETa = ETm; ETa<ETm when water supply is inadequate. ETm and ETa can be quantified for most crops and climates. It is possible to calculate relative yield losses if information on actual yield (Ya) in relation to maximum yield (Ym) under different water supply regimes is available to evaluate the impact of plant water deficit on yield decrease through the quantification of relative evapotranspiration (ETa/ETm).Ya = Ym when maximum water requirements are met, where economic conditions do not limit production and in a constraint-free atmosphere. When full water requirements are not met by available water supply, Ya<Ym (Jensen, 1968; Stewart *et al.,*1976).The four parameters (Ya, Ym, ETa, ETm) are related by a function called the water production function (Ky), which shows a linear relationship between relative yield decrease and relative evapotranspiration deficit (Vaus and Pruitt, 1983).

FAO's Irrigation and Drainage Paper 33 (Doorenbos and Kassam, 1979) and 66 (Steduto et al., 2012) have both published a lot on aspects of water relations in crop growth and attempts to understand crop response to water. Seasonal water production function values (Ky) recorded by FAO-33 for sugarcane crops are 0.75, 0.75, 0.5, 0.1 and 1.2 for initial, developmental, mid, late seasons and total growth periods, respectively (Doorenbos and Kassam, 1979). Whereas these values were stated by FAO-66 as 0.20/0.40, 1.20, 1.20, 0.10 and 1.20 (Steduto et al., 2012). The difference in the two FAO-documented Ky values may be due to experimental insufficiencies and climate changes, evapotranspiration and soil levels (Steduto et al., 2012). Furthermore, the FAO's water production functions are averaged over the entire globe.

However, for the semiarid area of India, there is no information on the stagewise water production functions and these values need to be established. The analysis was therefore formulated to determine the practical seasonal and stagewise water output values (Ky) for sugar cane.

2. Material and methods

2.1 Study region

The field experiment was performed at the research farm of the, Mahatma Phule Krishi Vidyapeeth, Rahuri, located in the western Maharashtra, India, during 2015 to 2017.The experimental site is situated at 19^o 47$^'$00" N latitude and 74^0 37$^'$00" E longitude at 657 m above mean sea level.

2.2 Regional climate

The area falls under the semi-arid and sub-tropical climate zones, with an average annual rainfall of 555 mm. Around 80% of the total annual rainfall is collected from the South-West monsoon (June to September), while the remainder is obtained from the North-East monsoon (October-November). The distribution of rain over 15 to 37 rainy days is unpredictable, irregular and poorly distributed. The annual mean maximum and minimum temperatures are 33 ^{0}C to 43 ^{0}C and 3.0 ^{0}C to 18 ^{0}C, respectively. The annual mean maximum and minimum relative humidity are between 59% and 90% and 21% and 61% respectively. The mean maximum and minimum relative humidity are 59 and 35%, respectively. The mean annual evaporation of the pan ranges from 5.3 to 12.1 mmday^{-1}, while the hours of sunshine vary from 7 to 9days^{-1}. The average annual wind speed is between 3.2 and 13.09 kmhr^{-1}. Agroclimatically, the location is in the drought prone area of Maharashtra.

Meteorological variables including temperature, relative humidity, pan evaporation, windspeed, solar sunshine hours and precipitation were measured with an automatic weather station located 50 m away from the plots. Phenological stagewise averages of meteorological variables for experimental period (12th December 2014 to 12nd December 2017) are given in Table 1.

2.3 Physical and hydraulic properties of soil

The experimental area's soil was clay. In reaction, the soil was medium alkaline (pH 8.36) with an electrical conductivity of 0.40 dS m^{-1}. The soil was 1.8 meters thick. The mean bulk density was 1.27 Mgm^{-3}, with 41.4 and 17 % soil moisture at field capacity and wilting point, respectively. Table 2 summarizes the soil physical and hydraulics properties. The ground water table was about 2 m below the ground surface. The source of irrigation was an open well. There was an open well for irrigation supply. The irrigation water pH, EC, was 7.79 and $0.60 dSm^{-1}$.

2.4 Experimentation and treatments

In combination of three irrigation quantities (100 %, 70 % and 40 %replenishment of soil water), twenty-seven treatments were evaluated during three referred phenological stages (development, mid-season and end) in such a way that the impact of the specified irrigation quantity can be independently analyzed at the specified phenological stage (Table 3). A two-

Years	Growth stages	Duration, days	Temperature (°C)	Relative humidity (%)	Sunshine hours
			Maximum	Minimum	Maximum
2015	Initial stage	0-52	27.8	10.5	57.1
	Development stage	53-128	34.5	17.0	53.9
	Mid season stage	129-287	34.0	22.6	67.8
	End stage	288-370	32.1	16.6	59.5
2016	Initial stage	0-46	30.7	11.1	50.0
	Development stage	47-128	37.4	19.4	42.3
	Mid season stage	129-294	32.3	22.8	71.5
	End stage	295-360	29.9	11.9	58.3
2017	Initial stage	0-41	29.7	11.7	61.5
	Development stage	42-114	36.2	16.3	40.8
	Mid season stage	115-279	33.7	22.7	71.5
	End stage	280-347	30.7	16.1	67.9

Table 1 Climatic characteristics of the experimental period in 2015, 2016 and 2017.

Soil layer depth, cm	Sand (%)	Silt (%)	Clay (%)	Textural class	Field capacity (%)	Permanent wil
0-15	7.2	29.7	58.5	Clay	39.1	16.4
15-30	7.4	30.7	59.7	Clay	40.3	16.6
30-45	8.1	33.4	63.1	Clay	43.7	17.3
45-60	8.6	31.3	61.5	Clay	42.1	17.8
60-75	7.5	32.1	61.2	Clay	41.8	16.7
Average	7.76	31.4	60.8	Clay	41.4	17

Table 2 Soil physical and hydraulic characteristics of experimental site

(Dingre and Gorantiwar, 2020)

Table 3 Definition of the treatments relative to various levels of soil water replenishment

Treatments	Target irrigation coefficient (Kit) relative to each treatment

		Development stage	Mid season
T_1	DS -1.00I, MSS-1.00I, ES-1.00I	1	1
T_2	DS -1.00I, MSS-1.00I, ES-0.70I	1	1
T_3	DS -1.00I, MSS-1.00I, ES-0.40I	1	1
T_4	DS -1.00I, MSS-0.70I, ES-1.00I	1	0.7
T_5	DS -1.00I, MSS-0.70I, ES- 0.70I	1	0.7
T_6	DS -1.00I, MSS-0.70I, ES- 0.40I	1	0.7
T_7	DS -1.00I, MSS-0.40I, ES-1.00I	1	0.4
T_8	DS - 1.00I,MSS- 0.40I, ES-0.70I	1	0.4
T_9	DS -1.00I, MSS-0.40I, ES-0.40I	1	0.4
T_{10}	DS-0.70I, MSS-1.00I, ES-1.00I	0.7	1
T_{11}	DS -0.70I, MSS-1.00I, ES-0.70I	0.7	1
T_{12}	DS -0.70I, MSS-1.00I, ES-0.40I	0.7	1
T_{13}	DS -0.70I, MSS-0.70I, ES-1.00I	0.7	0.7
T_{14}	DS -0.70I, MSS-0.70I, ES- 0.70I	0.7	0.7
T_{15}	DS -0.70I, MSS-0.70I, ES- 0.40I	0.7	0.7
T_{16}	DS -0.70I, MSS-0.40I, ES-1.00I	0.7	0.4
T_{17}	DS - 0.70I, MSS- 0.40I, ES-0.70I	0.7	0.4
T_{18}	DS -0.70I, MSS-0.40I, ES-0.40I	0.7	0.4
T_{19}	DS-0.40I, MSS-1.00I, ES-1.00I	0.4	1
T_{20}	DS -0.40I, MSS-1.00I, ES-0.70I	0.4	1
T_{21}	DS -0.40I, MSS-1.00I, ES-0.40I	0.4	1
T_{22}	DS -0.40I, MSS-0.70I, ES-1.00I	0.4	0.7
T_{23}	DS -0.40I, MSS-0.70I, ES- 0.70I	0.4	0.7
T_{24}	DS -0.40I, MSS-0.70I, ES- 0.40I	0.4	0.7
T_{25}	DS -0.40I, MSS-0.40I, ES-1.00I	0.4	0.4
T_{26}	DS - 0.40I, MSS- 0.40I, ES-0.70I	0.4	0.4
T_{27}	DS -0.40I, MSS-0.40I, ES-0.40I	0.4	0.4

replication randomized full block design was used. The development (TS), mid-season (GGS) and end stage (MS) respectively lasted 45-135, 135-300, and 300 to 360 days after planting (DAP). Farmers in this area primarily raised nursery to obtain distinct advantages such as good germination, careful plant selection, more time for field planning, and the saving of early irrigations etc. Hence, in this research, the initial stage was skipped.

2.5 Irrigation scheduling

Irrigation was timed to coincide with the replenishment of root zone soil water. The depth of water required for soil water replenishment was determined according to the following formula (Michael, 2010).

$d = \sum_{i=1}^{n} \frac{\mathrm{FC}_i - \mathrm{MC}_i}{100} \mathrm{X}\ \mathrm{BD}_i X D_i \ldots\ldots\ldots\ldots\ldots(1)$

FC_i= field capacity, % for i^{th} layer; MC_i= moisture content at the time of irrigation, %; BD_i = bulk density of soil, for i^{th} layer Mgm^{-3}; D_i = effective root zone depth, for ith layer cm; n = n is the number of soil layers in the root zone depth that were sampled (5).

The actual depths of irrigation were measured according to the treatments (Table 3). Before irrigation, the actual irrigation depth (I) for each treatment was determined using the formula below.

$$I = d\ X\ Kit \ldots\ldots\ldots\ldots(2)$$

Where, I = Irrigation depth of respective treatment (mm); Kit = Target irrigation coefficient relative to each treatment (1, 0.7 and 0.4 for 100, 70 and 40 % soil water replenishment respectively). The irrigation begins after 15 days of transplanting and ends before 15 days of harvesting.

2.5.1 Irrigation system used

Drip irrigation was used to irrigate the plants every 7-10 days. The drip irrigation system was made up of LLDPE laterals that were placed at center of the sugarcane plant rows and spaced at 150 cm, thus each irrigating single crop row. The emitter spacing was 50 cm, and the emitter flow rate was 4 L h^{-1} at pressure of 1 kg cm^{-2}. Discharges and pressure were regularly observed during the season and did not display any noticeable variations due to careful design and management. Each plot provided with a valve to control and measure irrigation water applications. Fertigation by water-soluble fertilizer was applied in 26 doses through fertigation of N, P_2O_5 and K_2O, which were 250, 115, and 115 kg ha^{-1}, respectively (Pawar *et.al.,* 2013). Each plot received the same fertilizer dose in all seasons.

2.6 Soil moisture measurements

The thermo-gravimetric approach was used to assess the soil moisture status. The destructive method was used to record the root length measurements. One healthy plant was carefully uprooted for each moisture content observation to determine the effective root zone. The soil around the plant was completely saturated before uprooting, and then plant was slowly removed. The sugarcane plant's maximum root penetration is reported as 100 cm (Jangpromma *et al.,* 2012), whereas, the bulk of roots were concentrated in the top 75-80 cm of soil, with only a few roots below 20 cm. Therefore, a root zone depth of 75 cm was considered when planning the observations. Soil samples were taken at each plot by soil auger, every 15 cm from 0 to 75 cm prior to irrigation and between two consecutive irrigations (roughly at the midpoint of the irrigation interval). The soil moisture was also checked whenever the soil profile was recharged by precipitation. The difference in soil moisture storage (ΔS) during each irrigation was calculated using the corresponding soil moisture content values.

2.7 Actual crop evapotranspiration

The actual evapotranspiration (ETa) was estimated for each treatment using a simplified soil water balance expressed as:

$$ETa = I + \ Pe \ \pm \ \ S \ - R - D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (3)$$

Where, Pe is the effective precipitation; ΔS is the difference in soil moisture storage in soil layers between two successive soil water measurements. Because of the flat topography of the experimental site, there was no surface runoff (R) during irrigation or precipitation cycles. Deep percolation (D) was also neglected as water applied for the highest irrigation depths was only sufficient to replenish soil water to field capacity, thus not enough to percolate through root zone; in addition, the drip irrigation system's water supply rate was slow, preventing deep percolation. The FAO 25 criteria (Dastane, 1974) were used to measure effective precipitation. All the water balance components are in mm.

2.8 Water production function

The seasonal water production function (Ky) was determined by standard procedure reported by FAO-33 (Doorenbos and Kassam, 1979) and FAO-66 (Steduto *et al.,* 2012) as presented by equation.

$$1 - \frac{\text{Ya}}{\text{Ym}} = K_y \left(1 - \frac{\text{ETa}}{\text{ETm}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The ETa and ETm are expressed in mm whereas Ya and Ym are expressed in t ha^{-1}.

2.8.1 Phenological stagewise water production functions

The crop phenological stagewise water production functions were calculated using Jensen's (1968) dated water production function by equation.

$$\frac{Y_a}{Y_m} = 1 - \sum_{s=1}^{n} K_{\text{ys}} \left(\frac{\text{ET}_{\text{ms}} - \text{ET}_{\text{as}}}{\text{ET}_{\text{ms}}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where, ET_{ms} and ET_{as} are maximum and actual crop evapotranspiration during s^{th} crop phenological stage, mm; Kys= Stage water production function; n= total number of phenological stages (3).Using the relative decrease in crop evapotranspiration (1-ETa/ETm) of different phenological stages as an independent variable and the relative decrease in yield (1-Ya/Ym) of schedules as a dependent variable, the values of phenological stage wise water production function (Ky_1-development, Ky_2 – mid-season and Ky_3-end stage) were calculated using multiple linear regression analysis.

....................(6)

2.9 Planting material and crop management

Sugarcane seedlings (cultivar CoM-265) were prepared in the nursery and transplanted at a single-row spacing of 1.50 x 0.60 m after forty days. During nursery raising period, common irrigations were applied at every alternate day based on climatological approach (Allen *et al.,* 1998). The crop coefficient was determined to be 0.4 for common irrigation. Likewise, after seedling transplantation, all treatments received daily irrigation for the next two weeks until the seedling was established. The net plot size wise was 13.5 m x 6 m. The other field management practices were performed uniformly according to the best management practices (Dingre and Gorantiwar, 2021).

1. **Results and Discussion**

3.1 Irrigation water applied

The numbers of irrigations during development, mid-season and end stage varied in 2015 (9, 10 and 3), 2016 (10, 9 and 4) and 2017 (8, 7 and 3) as a fact of skipping of irrigation event during incidence of precipitation in respective season. However, significant variations in seasonal irrigation depths were noticed between the treatments over the seasons. The seasonal irrigation depths in 2015 ranged from 713 to 1173 mm; 434 to 809 mm in 2016; and 453 to 918 mm in 2017.Irrigation treatment T_1 (967 mm) had the highest average irrigation depth over three years, while irrigation treatment T_{27} had the lowest (533 mm).Climate demand, which is represented by temperature, relative humidity, sunshine hours, wind speed and evaporation (Table 1) caused total irrigation water amounts to be lower in 2016 than in 2015 and 2017.Further, the differences in irrigation depth for phenological stages in a season were also noted due to differences in usage of crop water and duration of stage. However, within a phenological stage the treatments with the same amount of deficit emerged with slight variations in irrigation quantities (Table 4).

Invariably in all seasons, mid-season stage was identified as high-water requirement stage due to its long duration (165-170 days) followed by development (75-80 days) and end stage (65-70 days). Because of the low contribution of precipitation in crop water use, larger irrigation depths were applied in the mid-season stage in 2015 than in 2017 and 2016 (Table 4). Interestingly, higher irrigation water depths given in development stage of 2016 than rest of two seasons (Table 1). Lowest irrigation depths applied in end stage was because of decline in water use with crop maturity and rich soil moisture content after end of monsoon rains. Dingre and Gorantiwar (2020) reported decline in crop evapotranspiration (ETa) during this period as a reason that crop taking advantage of soil moisture stored from precipitation.

3.2 Effective Precipitation

Table 4 Irrigation water depths (mm) applied to different deficit irrigation treatments of sugarcane during 2015, 2016, 2017seasons and average of 3 years.

Treatments	2015	2016	2017	3 years average
T_1	1173.3	808.3	918.1	966.6

Treatments	2015	2016	2017	3 years average
T_2	1137.0	777.6	902.1	938.9
T_3	1098.4	736.4	877.1	904.0
T_4	1025.0	700.7	772.6	832.8
T_5	1012.1	670.1	756.6	812.9
T_6	965.7	644.2	731.6	780.5
T_7	799.5	548.2	617.2	655.0
T_8	784.6	522.0	601.2	635.9
T_9	723.0	476.4	576.2	591.9
T_{10}	1127.5	774.6	867.5	923.2
T_{11}	1114.1	738.3	851.6	901.3
T_{12}	1067.7	701.3	826.6	865.2
T_{13}	998.4	660.1	722.1	793.5
T_{14}	970.7	642.4	706.1	773.1
T_{15}	945.9	602.6	681.1	743.2
T_{16}	766.9	506.0	566.6	613.2
T_{17}	754.4	497.6	550.6	600.9
T_{18}	729.5	451.7	525.6	568.9
T_{19}	1065.2	696.7	794.5	852.1
T_{20}	1060.9	656.0	778.5	831.8
T_{21}	1012.8	625.7	753.5	797.3
T_{22}	974.4	576.3	649.0	733.2
T_{23}	959.6	568.5	633.0	720.4
T_{24}	910.3	521.4	608.0	679.9
T_{25}	766.7	467.6	493.5	575.9
T_{26}	755.5	451.3	477.6	561.5
T_{27}	712.8	434.7	452.6	533.4

The FAO 25 criterion (Dastane, 1974) was not used due to low precipitation depths in total experimentation period. In all three seasons, no precipitation event had a depth significant enough to replenish the soil water to the field capacity. Because of the continuous and adequate supply of irrigation, 100 % replenishment required less water depths (d) to replenish soil water to field capacity; therefore, all precipitation events were described as effective.

Obviously, treatments other than 100 % replenishment needed greater water depths (d) to replenishment soil water due to inadequate irrigations. Thus, precipitation amount effective for 100 % replenishment treatment was considered to be effective for all other treatments. Nevertheless, the irrigation depths of treatments were influenced by precipitation incidence in all three seasons.

3.3 Actual sugarcane crop evapotranspiration

The ETa determined from root zone soil water balance differed depending on the treatment (Table 5). In all growing seasons, the non-stressed T_1 had largest ETa, whereas the most stressed treatment T_{27} registered the smallest ones. The ETa treatment of 100% soil water replenishment (T_1) was 1387mm, 1291 mm, 1292 mm and 1323 mm respectively for 2015, 2016, 2017 and an average of all seasons. The values for that 70 % water application throughout season (T_{14}) were 1173 mm, 1106 mm, 1085 mm, 1121 mm whereas 40 % water application throughout season (T_{27}) were 908 mm, 874 mm, 836 mm,873 mm respectively.

Total sugarcane crop evapotranspiration varies considerably from place to place depending on weather conditions, texture of soil and duration (Thompson, 1976). Few studies are, however, reported about the seasonal sugarcane evapotranspiration for Indian conditions (Singh *et al.,* 2006, Tiwari, 2006, Singh *et al.,* 2007, Shrivastava *et al.,* 2011, Bhunia *et al.,* 2013, Bhingardeve, 2017, Nimbalkar, 2017). However, its estimation depends largely on the researchers' methodology. The

Irrigation Treatment	Development stage	Mid season stage	End stage	Seasonal			
	2015	2016	2017	Average	2015	2016	2017
T_1	267.3	261.1	197.5	242.0	938.7	834.5	906.3
T_2	266.4	258.9	191.7	239.0	929.4	830.8	899.8
T_3	260.6	256.0	194.4	237.0	937.6	829.3	903.1
T_4	265.4	254.6	194.2	238.1	790.2	733.6	770.1
T_5	265.0	254.8	200.2	240.0	801.9	725.7	772.0
T_6	261.0	252.1	200.9	238.0	806.1	742.4	782.4
T_7	267.1	255.7	194.8	239.2	564.0	582.7	621.1
T_8	264.3	254.5	194.9	237.9	565.6	586.1	623.6
T_9	258.1	250.6	189.5	232.7	558.5	584.0	619.0
T_{10}	228.9	220.1	158.1	202.4	934.9	829.6	901.9
T_{11}	230.2	211.7	154.9	198.9	936.9	826.1	901.2
T_{12}	221.0	216.4	156.7	198.0	935.8	821.2	898.2
T_{13}	231.3	209.9	157.4	199.5	795.2	721.3	766.5
T_{14}	228.3	212.4	155.3	198.7	788.6	726.6	765.8
T_{15}	230.5	215.7	163.8	203.3	802.3	722.4	770.6
T_{16}	224.3	215.9	156.9	199.0	562.2	573.0	615.4
T_{17}	227.4	217.7	158.8	201.3	564.0	584.2	621.9
T_{18}	226.7	214.2	159.6	200.2	569.3	584.0	624.4
T_{19}	159.3	146.1	67.0	124.1	937.5	804.9	890.9
T_{20}	167.1	137.8	99.8	134.9	929.0	801.0	884.7
T_{21}	160.6	139.9	103.7	134.7	934.8	801.9	888.0
T_{22}	163.1	134.7	120.2	139.3	824.5	692.0	766.5
T_{23}	164.4	140.4	123.3	142.7	825.1	692.8	767.1
T_{24}	166.3	135.3	116.3	139.3	816.1	700.8	766.7
T_{25}	164.1	147.6	131.2	147.6	607.3	580.0	641.4
T_{26}	169.6	147.7	130.1	149.1	605.1	585.1	642.8
T_{27}	173.5	143.6	126.4	147.8	601.8	596.7	647.0

Table 5 Actual evapotranspiration (mm) of sugarcane in development, mid season, end stages and seasonal under different deficit irrigation treatments during 2015, 2016, 2017 seasons and average of 3 years.

water usage for conventional irrigation in canal command area has reported as 2500 mm for seasonal sugarcane crop (Shrivastava *et al.,* 2011). Tiwari (2006) measured water usage as 1743 mm, including 264 mm effective precipitation, using an irrigation water (IW) to cumulative pan evaporation (CPE) ratio method. Similarly, Singh *et al.,* (2006) indicated 1575 mm water use of sugarcane crop for subtropical northern India using 0.8 IW/CPE ratio. However, Singh *et al.,* (2007) reported 1233 mm water use for seasonal sugarcane grown in same conditions on 1.0 IW/CPE ratio. Alike, Bhunia *et al.,* (2013) on same 1.0 IW/CPE ratio, reported water use of seasonal sugarcane as 1578 mm in sandy loam soils of subtropical Rajasthan, India. The effect of the IW/CPE method, however, is that at the beginning of the crop season, there is a large irrigation depth and a smaller depth during the peak use of water.

On other hand, Bhingardeve (2017) and Nimbalkar (2017) used pan evaporation approach and reported water use of sugarcane as 1136 mm (including 147 mm precipitation) and 1072 mm (including 173 mm precipitation), however the role of effective precipitation in crop development is debatable. This can be avoided by measuring the soil water balance for the actual root zone, which clearly demonstrates the role of precipitation in the soil. Overall, the sugarcane evapotranspiration ranges from 1000 to 1800 mm depending on the method used by researchers. Therefore, sugarcane evapotranspiration amounting 1323 mm derived in this investigation seems to be appropriate for semiarid conditions. In addition, nursery planting that saved three early irrigations amounting 80 mm each is encouraged in this investigation.

3.4 Yield decrease over full irrigation

In comparison to other treatments over three seasons, the highest sugarcane yield (Ym) was obtained in non deficit T_1 owing to 100 % soil water replenishment throughout season. The variations in yield decrease between T_1 and T_2 of water deficit treatments (Table 6) are due to the effects of irrigation depths and water deficit timing on yield (Inman Bamber, 2004;Kumar *et al.* 2005).In the first season, yield decreases over T_1 ranged from 0.7 to 48.4%, with the largest reduction in treatment T_{27} (48.4 %).During the mid-season stage, treatments with a high water deficit showed a greater decrease in yield (T_7- T_9, T_{16}-T_{18} and T_{25}-T_{27}).This was mainly because of low water application during peak water use of crop that resulted into inferior yield (Ramesh, 2000).Water is needed for almost all plant processes, and its lack in any process has a negative impact on growth, production, and cane yield, as most processes are interconnected (Ellis and Laukford, 1990; Inman-Bamber and Smith, 2005).

The development stage was observed as next sensitive stage after mid-season (Table 6). The treatments had 100 % soil water replenishment in development stage (T_7, T_8 and T_9) had 30.4, 33.7 and 36.7 % yield decrease over T_1, respectively. This yield decrease increased slightly to 33.2, 36.7 and 40.2 % in treatments received 70 % soil water replenishment in development stage (T_{16}, T_{17} and T_{18}), respectively. In a different way, treatments which had 40 % soil water replenishment during development stage and followed by 100 % replenishment in mid-season stage ($T_{19,}$ $T_{20}$and T_{21}) come out with less yield decrease of 12.9, 13.8 and 15.2 % respectively. This may be due to the fact that water stress during the development stage can be compensated during the cane elongation period, resulting in increased cane yield, if complete recovery occurs during the next mid-season stage, when water requirements are met (Ramesh and Mahadevaswamy, 1999). The end stage was discovered to be the least water sensitive. The results showed that the treatments under 40 % soil water replenishment in mid-season and end stage (T_9, T_{18} and T_{27}) registered greater yield decrease (36.7, 40.2 and 48.4 % respectively). On the other hand, a small reduction in yield was observed when 40 % soil water replenishment in the grand growth stage was switched to 100 % replenishment (T_7, T_{16} and T_{25}) and 70 % replenishment (T_8, T_{17} and T_{26}) in the maturity stage. However, the yield

Treatments	% yield reduction	% reduction in irrigation water	% reduction in total water use	
	2015	2016	2017	Average
T_1	0	0	0	0
T_2	0.7	0.7	0.8	0.7
T_3	2.3	1.7	1.7	1.9
T_4	11.0	6.9	9.2	9.1
T_5	11.4	7.9	10.1	9.8
T_6	13.3	8.6	11.0	11.0
T_7	30.4	20.3	25.4	25.5
T_8	33.7	20.6	26.9	27.2
T_9	36.7	21.1	29.0	29.1
T_{10}	3.8	6.6	5.3	5.2
T_{11}	5.0	7.2	5.7	5.9
T_{12}	7.8	9.1	8.4	8.4
T_{13}	11.6	15.4	12.6	13.2
T_{14}	12.6	15.9	13.6	14.0
T_{15}	14.1	16.4	14.3	14.9
T_{16}	33.8	25.5	29.9	29.8
T_{17}	36.7	27.0	32.3	32.1
T_{18}	40.2	30.9	35.2	35.5
T_{19}	5.0	18.4	16.0	12.9
T_{20}	6.6	18.7	16.7	13.8
T_{21}	8.2	20.0	18.2	15.2
T_{22}	22.9	25.2	23.7	23.9
T_{23}	23.7	25.5	24.4	24.5
T_{24}	25.0	26.3	25.5	25.6
T_{25}	42.2	30.5	36.8	36.6

Treatments	% yield reduction	% reduction in irrigation water	% reduction in total water use	
T_{26}	44.4	31.3	37.9	38.0
T_{27}	48.4	32.8	40.4	40.7

Table 6. Percent reduction in sugarcane yield, irrigation water and total water use for different treatments over no stress treatment in 2015, 2016, 2017 and 3 years means.

decrease difference between 100 % and 70 % soil water replenishment was almost negligible. The trends of yield decrease were similar in another two seasons (Table 6). In 2016 and 2017, the range of yield decreases over T_1 was shortened to 0.7 to 32.8 % and 0.8 to 40.4 %, respectively. Furthermore, due to substantial rainfall obtained during the grand growth stage of 2016 and 2017, the yield gap of treatments with 40 % soil water replenishment in mid-season stage (T_7- T_9, T_{16}-T_{18} and T_{25}-T_{27}) was decreased. The precipitation contributed to peak water use during mid-season which favored yield parameters to some extent and ultimately reduced the yield difference with T_1. The difference between yield decreases of 100% soil water replenishment in end stage (T_7, T_{16} and T_{25}) and 70 % soil water replenishment (T_8, T_{17} and T_{26}) was not considerable. However, maximum reduction registered in treatment T_{27} in all seasons.

3.5 Irrigation water saving over full irrigation

The irrigation water saving over 100 % soil water replenishment treatment (T_1) was observed in range of 3.1 to 39.2 % in 2015; 3.8 to 46.2 % in 2016 season and 1.7 to 50.7 % in 2017.Over the course of three years, the average irrigation water savings over complete irrigation treatment ranged from 2.9 to 44.8 % (Table 5). During the 2015, 2016 and 2017 seasons (T_{14}), the irrigation water savings for 70 % soil water replenishment were 17.3, 20.5, and 23.1 %, respectively. For 40 % soil water replenishment during the season (T_{27}), the corresponding values were 39.2, 46.2, and 50.7 %, respectively.

3.5.1 Overall water saving over full irrigation

Because of the contribution of precipitation and soil moisture storage in overall water use, Overall water savings over 100 % soil water replenishment (T_1) related to all treatments dropdown over irrigation water savings (Table 6). In the 2015 season, Overall water savings ranged from 2.1 to 34.5 %, while in the 2016 season, it ranged from 2.8 to 32.3 %. In the 2017 season, Overall water saving was observed in the range of 0.2 to 35.3 %. The average water saving 1.7 to 34.1 %.

The overall water saving for treatment 70 % soil water replenishment throughout season during 2015, 2016 and 2017 were nearly equal as 15.5, 14.3and 16 %, respectively. The increase values of water saving for 40 % soil water replenishment throughout season in corresponding years were 34.5,32.3 and 35.3 %, respectively (Table 6). The water saving mainly varied due to differences in precipitation amount of three years. In 2016 and 2017, the water savings of high deficit treatments over T_1 slightly compensated by precipitation occurred in mid-season. In 2015, drier regime due to limited availability of moisture in these treatments resulted into higher irrigation depth which reduced Overall water saving.

1. *Seasonal water production function*

Since there was no lack of water in treatment T_1 (100 % soil water replenishment during the season), actual evapotranspiration (ETa) was highest (ETm). The ETm during 2015, 2016, 2017and average of three years were 1387, 1291, 1292 and 1323 mm respectively. Over the seasons, actual evapotranspiration (ETa) of T_2 to T_{27} treatments differed in terms of the amount of soil water replenished, precipitation, and growth stages. Deficit irrigation had a distinct effect on sugarcane yield, which was represented by a linear relationship between relative evapotranspiration decrease and relative yield decrease (Fig.1). The seasonal water production functions (Ky) determined for 2015, 2016, 2017 were 1.18, 1.05 and 1.09 respectively. The differences in Ky value for three seasons was chiefly because of difference in precipitation amount precipitated in mid-season stage of particular year. In first year, the scanty precipitation (313 mm) during most sensitive cane elongation period (mid-season stage) caused greater relative decrease in yields in highly water deficit schedules; thus, elevated value of Ky to 1.18. In comparison, near-

[CHART]

Figure 1 Relationship between reduction in relative sugarcane yield to reduction in relative evapotranspiration during 2015-16, 2016-17 2017-18 seasons and average of 3 years.

[CHART]

(a) Present study

[CHART]

1. **Documented by FAO 33**

Figure 2 Comparison of stage wise yield response factor (Ky) for sugarcane developed under investigation with FAO-33.

normal rainfall (534 mm) in the second year aided in improving yields of water deficit schedules and lowering Ky to 1.05. The 2017 season also showed the similar trend and Ky slightly hiked to 1.09. Singh *et al.* (2011) indicated favorable effects in growth and yield due to timely rains for sugarcane under semiarid conditions. The average seasonal Ky value for sugarcane was found as 1.11. When the crop's water requirements aren't met, Ky values greater than 1 indicate that the crop will loss more yield (Doorenbos and Kassam, 1979; Steduto *et al.,* 2012). Overall, results indicated a big impact of soil-water deficit on the sugarcane yield; highlighting importance of water management in sugarcane at all stages of plant growth.

Our study yielded slightly lesser Ky value (1.11) than FAO-33 and FAO-66 reported value (1.20). This is mainly because of fact that Ky value affected by factors such as different crop growth periods, climate, magnitude of maximum evapotranspiration, soil, crop variety, fertilizer, salinity, pests and diseases, and agronomic practices (Najarchi *et al.,* 2011).

3.6.1 Stage wise water production functions

Invariably in all seasons, mid-season stage was noticed with high cropevapotranspiration due to its long duration (165-170 days) and peak water use. The development stage (75-80 days) is then followed by the end stage (65- 70 days). Multiple regression analysis enabled the development of water production functions from relative yield reductions with respect to deficit irrigation when water deficits occurred at different crop stages of sugarcane (Fig. 2 a). The water production function for sugarcane crop during development, mid-season and end stages in first year were 0.33, 0.88 and 0.10, respectively whereas corresponding values for second year were 0.31, 0.63, 0.05 and third year 0.32,0.87 and 0.07. The average values of three years were 0.31, 0.76 and 0.07, respectively.

Water deficits were most noticeable during the mid-season and development stages, while deficits during the end stage had little effect on crop yield.However, due to the length of each stage, the impact of water deficit on yield is not entirely unrecoverable in subsequent stages (Table 1).Based on graphical comparison with FAO-33 (Fig.2), the water production functions for development and mid-season stagecalculated in this research (0.31 and 0.76) was different than the values reported by FAO-33 (0.75 and 0.50).The variation in planting season may be a reason of difference in development stage Ky value whereas coinciding of monsoon rains might differ the mid-season stage Ky value under Indian semiarid conditions.

1. **Summery**

In sugarcane, applying less water than necessary during certain phenological stages that are more tolerant than others in order to maximize water use must be practiced for proper irrigation management in a limiting water situation. It is inevitable to generate knowledge of water production function (Ky)for this purpose; and this investigation specially emphasized on this aspect. The seasonal water production function was calculated using linear regression analysis to relate relative yield decreases (1-Ya/Ym) to relative evapotranspiration deficit (1-ETa/ETm). According to the findings, water stress is highly sensitive to sugarcane production during the mid-season and growth stages, but not so much during the end stages. The sugarcane crop's relative yield decreases were proportionally greater as the evapotranspiration deficit increased. The 3 years average seasonal Ky for sugarcane was found to be 1.11, compared to 1.20 in FAO-33 and FAO-66. For the development, mid-season, and end stages, the average Ky values were 0.31, 0.76, and 0.07, respectively. The development and mid-season stage water production functions were observed different with FAO-33 values (0.75 and 0.50) and FAO-66 (1.20). The water production functions developed in this study could be used for irrigation design, scheduling and water resources planning for sugarcane in the semiarid India.

1. **References**

Allen R. G., Pereira L. S., Raes D. and Smith M. (1998). Crop evapotranspiration. *FAO Irrigation and Drainage paper No.56*, FAO. Rome, pp.91-165.

Bhingardeve S.D., Pawar D. D, Dingre S. K. and Hasure R.R. (2017). Water productivity in sugarcane under subsurface drip irrigation. *International Journal of Agriculture Sciences.* 9(29): -4377-4381.

Bhunia S.R., Chauhan R.P.S. and Yadav B.S. (2013). Effect of planting geometry and drip irrigation levels on sugarcane (*Saccharum Officinarum*) yield, water use efficiency and cane quality under transgenic plains of Rajasthan. *Journal of Progressive Agriculture,* 4(1):102-104.

Carr M. K. V. and Knox J. W. (2011). The water relations and irrigation requirements of sugar cane (*Saccharum officinarum*): a review. *Experimental Agriculture*, 47 (1):1–25.

Commission for Cost and Prices (CACP) (2019). Price policy for sugarcane, 2019-20 Sugar season. Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi, pp. 26-27.

Dastane N.G. (1974). Effective rainfall in irrigated agriculture. *FAO Irrigation and Drainage Paper No. 25*. Rome.

Dingre S.K. and Gorantiwar S.D. (2020). Determination of the water requirement and crop coefficient values of sugarcane by field water balance method in semiaridregion. *Agricultural Water Management*, 232, 106042.

Dingre S.K. and Gorantiwar S.D. (2021). Soil moisture based deficit irrigation management for sugarcane (Saccharum officinarum L.) in semiarid environment, *Agricultural Water Management,* 245,106549.

Doorenbos J. and Kassam A.H. (1979). Yield response to water. *FAO Irrigation and Drainage Paper No.* 33, FAO, Rome, Italy. pp193.

Ellis R.D. and Laukford B.A. (1990). The tolerance of sugarcane to water stress during its main development phases. *Agricultural Water Management*, 17:117-128.

English M (1990). Deficit irrigation I: Analytical framework. J. Irrigation Drainage Eng., 116(3): 399-411.

English M. and Raja S.N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management,* (32): 1-14.

Garkar R.M., Bharud R.W. and Mate S.N. (2011). Effect of water stress on chlorophyll, nitrate reductase activity and cane yield in sugarcane (*Saccharum officinarum* L.). *Journal of Sugarcane Research*, 1(2): 43-49.

Hargreaves G.H. and Samani Z.A. (1984). Economic consideration of deficit irrigation. *Journal of Irrigation and Drainage Division ASCE*, 110: 343-358.

Hirwe N. A. and Jadhav A. S. (2009). Economic feasibility and water productivity by alternative cropping sequences to sugarcane under different irrigation methods. *Annals of Agriculture Research,* New series. 30 (3 & 4):136-141.

Inman Bamber N.G. (2004). Sugarcane water stress criteria for irrigation and drying off. *Field Crops Research*, 89: 107–122.

Inman-Bamber N.G. and Smith D.M. (2005). Water relations in sugarcane and response to water deficits. *Field Crops Research*, 92(2-3): 185–202.

Jangpromma N., Thammasirirak S., Jaisil P. and Songsri P. (2012). Effects of drought and recovery from drought stress on above ground and root growth, and water use efficiency in sugarcane (*Saccharum officinarum*L.). *Australian Journal of Crop Science*, 6(8):1298-1304.

Jensen M. E. (1968). Water Consumption by Agricultural Plants. In T. T. Kozlowski (ed) Water Deficit and Plant Growth. 11, Academic Press, New York.

Kumar M.D., Chalapathi K., Channabasappa K.S. and Patil S.G. (1999). Management of sugarcane (*Saccharum officinarum*) under moisture stress conditions of Tungabhadra Project area. *Indian Journal of Agronomy*, 4(4): 673-677.

Michael A. M. (2010). Irrigation: Theory and Practice (3rd Ed.) Vikas Publishing House Pvt. Ltd., New Delhi, pp. 465-472.

Najarchi, M., Kaveh, F., Babazadeh, H. and Manshouri, M. Determination of the yield response factor for field crop deficit irrigation. African Journal of Agricultural Research. 6(16): 3700-3705.

Nimbalkar R.R. (2017). Deficit irrigation scheduling through drip for sugarcane under different planting techniques. An unpublished Ph.D. Thesis submitted to MPKV, Rahuri.

Pawar D. D., Dingre S. K. and Durgude A. G. 2014. Enhancing nutrient use and sugarcane (*Saccharum officinarum*) productivity with reduced cost through drip fertigation in western Maharashtra.*Indian Journal of Agricultural Sciences,*84 (7): 844–849.

Pawar D. D., Dingre S. K. and Surve U. S. 2013. Growth, yield and water use in sugarcane (*Saccharum officinarum*) under drip fertigation. *Indian Journal of Agronomy,* 58(2):16-21.

Ramesh P. (2000). Water use and yield in sugarcane (*Saccharum officinarum*) varieties under varying soil moisture regimes. *Indian Journal of Agricultural Science*, 70 (6): 410-412.

Ramesh P. and Mahadevaswamy M. (1999). Effect of formative phase drought on yield attributes, yield and water use efficiency of sugarcane (*Saccharum officinarum*) varieties. *Indian Journal of Agronomy*, 44(4): 841-845.

Shrivastava A. K., Srivastava A. K. and Solomon S. (2011). Sustaining sugarcane productivity under depleting water resources. *Current Science*, 101(6):748-754.

Shukla, S.K. and Lal, M. 2003. Effect of sett size planting, method and soil moisture regime on growth and yield of sugarcane. *Indian Journal of Agricultural Sciences*, 73: 534-537.

Singh P.N., Shukla S.K. and Bhatnagar V.K. (2007). Optimizing soil moisture regime to increase water use efficiency of sugarcane (Saccharum spp. hybrid complex) in subtropical India. *Agricultural Water Management*, 90(2): 95-100.

Singh R.D., Singh P.N. and Kumar A. (2006). Evaluation of sugarcane *(Saccharum officinarum* L.) genotypes under variable water regimes. *Indian Journal Crop Science*, 1(1-2): 142-145.

Stewart J. I., Hagan R. M. and Pruit W. O. (1976). Production functions and predicted irrigation programs for principal crops as required for water resources planning and increased water use efficiency. Final Report, U. S. Dept. of Interior. Bur. of Reclamation, Washington, D. C.

Thompson, G.D. 1976. Water use by sugarcane, 371. Waltham: Chronica Botanics.

Tiwari K.T. (2006). Water stress management in *Suru* sugarcane. An unpublished P.HD. Thesis submitted to MPKV, Rahuri.

Vaus H.J., Pruit W.O. (1983). Crop water production functions. In: Hillel D. (Ed.) advance in irrigation. Academic Press New York, 2: 61-97.