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Estimating yield of sorghum using root zone water balance model and spectral characteristics of crop in a dryland Alfisol

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ABSTRACT

This study investigated the relationship between sorghum grain yield for a range of soil depths, with the seasonal crop water stress index based on relative evapotranspiration deficits and spectral vegetation indices. A root zone water balance model was used to evaluate seasonal soil water fluctuations and actual evapotranspiration within a toposequence; soil depth varied between 30 and 75 cm and available water capacity ranged from 6.9 to 12.6% (v/v, %). An empirical model was used to determine root growth. Runoff was estimated from rainfall data using the curve number techniques of the Soil Conservation Services, combined with a soil water-accounting procedure. The high r^2 values between modeled and observed values of soil water in the root zone ($r^2 > 0.70$, significant at $P < 0.001$) and runoff ($r^2 = 0.95$, significant at $P < 0.001$) indicated good agreement between the model output and observed values. Canopy reflectance was measured during the entire crop growth period and the following spectral indices were calculated: simple ratio, normalized difference vegetation index (NDVI), green NDVI, perpendicular vegetation index, soil adjusted vegetation index (SAVI) and modified SAVI (MSAVI). All the vegetation indices, except for the perpendicular vegetation index, measured from booting to anthesis stage, were positively correlated with leaf area index (LAI) and yield. The correlation coefficient for spectral indices with dry biomass was relatively less than for LAI and yield. Modified SAVI recorded from booting to milk-grain stage gave the highest average correlation coefficient with grain yield. Additive and multiplicative forms of water-production functions, as well as water stress index calculated from water budget model, were used to predict crop yield. A multiple regression was carried out with yield, for the years 2001–2003, as the dependent variable and MSAVI, from the booting to the milk-grain stage of crop and relative yield values, calculated using both additive and multiplicative water production functions as well as water stress index, as the independent variables. The multiplicative model and MSAVI, recorded during the heading stage of crop growth, gave the highest coefficient of determination ($r^2 = 0.682$, significant at $P < 0.001$). The multiple regression equation was tested for yield data recorded during 2004; the deviation between observed and estimated yields varied from −6.2 to 9.4%. The water budget model, along with spectral vegetation indices, gave satisfactory estimates of sorghum grain yields and appears to be a useful tool to estimate yield as a function of soil depth and available water.

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1. Introduction

The ability to accurately predict the yield of field crops allows producers, economic agencies, and buyers to make decisions with respect to crop management, pricing, and available markets. Other than genetic factor the factors associated with grain yields include soil characteristics (e.g. texture, bulk density, organic matter, nutrient levels), agronomic inputs (fertilizers and soil amendments), field scale management (tillage, drainage and irrigation) and meteorological effects. However, while simulation models can predict yield relatively accurately under ideal conditions, they are much less accurate when the plant suffers stress due to diseases and pests, weed growth, and nutrient and soil water deficiencies.

In dryland/rainfed regions, water has long been considered to be the main limiting resource for crop growth and yield. Although water is limiting, it is often the distribution of water rather than lack of total seasonal amounts that affects crop growth and final yields (Monteith, 1991). Dryland crops frequently suffer crop water stress (i.e. deficit of plant accessible soil water) because of uneven seasonal distribution of rainfall, which may subsequently affect the yield adversely. Actual crop water stress will depend on rainfall partitioning, the water holding capacity of the soil, crop water demands, antecedent soil water content and crop water uptake capacity, and requires at least a simple water balance analysis for calculating all of these components (Barron et al., 2003).

The magnitude of crop water stress/deficit is assessed in terms of the extent by which the actual evapotranspiration (AET) falls short of its potential value (PET) or that the actual soil water content is short of a critical threshold value. A simple water budget model is effective to estimate the availability of water to the crop to meet evapotranspiration. The model only requires knowledge of soil water-holding capacity, rooting depth, crop growth stages, and weather data (Timlin et al., 2001; Victor et al., 1988). The specific indices used to quantify water stress to crop are relative evapotranspiration (AET/PET), relative evapotranspiration deficit (1 − (AET/PET)), or soil moisture deficit (SMD). The effects of stress, as defined by these indices, interact in a complex manner during different periods of the growing season. The combined effect of stress effects in several periods is evaluated by postulating that these effects are additive or multiplicative. Both additive and multiplicative forms of the water production function can predict crop yields within reasonable limits (Rao et al., 1988). While plant available water is a major determinant for crop yields, yield prediction-using crop available water might not give a better picture as other impacts, such as pests and diseases, crop management factors etc., also contribute variability to the yield (Rao and Saxton, 1995).

Remote sensing techniques, in particular multispectral reflectance, can provide an instantaneous, nondestructive, and quantitative assessment of the crop's ability to intercept radiation and estimate for stress and crop yield (Ma et al., 1996; Clevers et al., 1994; Clevers, 1997). Numerous spectral vegetation indices have been developed to characterize vegetation canopies. The most common of these indices, which utilize red and near infrared (NIR) wavelengths, are the simple ratio of infrared to red, or normalized difference vegetation index (NDVI) (Tucker, 1979), or its linear combination i.e., the perpendicular vegetation index (Richardson and Wiegand, 1977). These indices have been found to be well correlated with various vegetation parameters including green leaf area, biomass percent green cover, productivity, and photosynthetic activity (Colwell, 1974; Hatfield et al., 1984; Asrar et al., 1984; Sellers, 1985). Gitelson et al. (1996) proposed a green normalized difference vegetation index (GNDVI), where the green band is used in the equation for NDVI instead of the red band, and showed that the green band, in combination with the NIR band, is more closely associated with the variability in leaf chlorophyll, nitrogen content, and grain yield than the red band.

A number of physical and plant anatomical factors can affect reflectance measurements. When the crop does not cover the entire soil surface, reflectance measured from a certain height above ground level will represent the reflectance of the canopy and the soil surface rather than just the crop itself (Ma et al., 2001). Soil brightness influences have been noted in numerous studies where, for a given amount of vegetation, darker soil substrates resulted in higher vegetation index values when the ratio vegetation index or the NDVI were used as vegetation measures (Colwell, 1974; Elvidge and Lyon, 1985; Huete et al., 1985). A soil adjusted vegetation index (SAVI) was developed to minimize soil influences on canopy spectra by incorporating a soil adjustment factor, L, in the denominator of the NDVI equation. For optimal adjustment of the soil effect, however, the L factor should vary inversely with the amount of vegetation present. A modified SAVI that replaces the constant L in the SAVI equation with a variable L function is presented by Qi et al. (1994). These vegetation indices, calculated from canopy reflectance showing spatial and temporal variation resulting from soil and crop characteristics, are important sources of data for making yield maps (Chang et al., 2005).

Grain sorghum (*Sorghum bicolor* (L.) Moench), a well-adapted crop for southern India, is grown extensively under dryland conditions in Alfisol. Yields of the dryland sorghum are strongly influenced by plant-available soil water content at planting and by growing season rainfall.

The presented analysis in this paper deals with sorghum yield estimation within an Alfisol toposequence using two different approaches: (i) a simple water balance model where additive and multiplicative forms of water production functions are used to predict yield, and (ii) using the spectral characteristics of the crop. Efforts have been made to obtain a better estimation of yield by combining both the water balance approach and use of the spectral characteristics of the crop.

2. Materials and methods

2.1. *Development of a root zone soil water balance model*

A simple root zone soil water balance model is used for estimating the actual evapotranspiration (AET). Here the soil reservoir is divided into two layers: (i) an active layer of depth in which roots are present at any given time and from which both water extraction and drainage would occur, and (ii) a passive layer of depth [maximum root depth – root depth attained any day after sowing (DAS)] from which only drainage would occur. The two layers are distinct in the initial phase of crop growth, and their relative depths are governed by the rate of root growth. However, once the maximum root depth is attained, the entire root zone becomes only one layer. Rainwater, in excess of field capacity (FC), will percolate to the lower passive layer and is instantaneously redistributed within it. Water in excess of the FC of the passive layer drains out of it as deep percolation. If the updated water balance is less than or equal to the water content at the permanent wilting point (PWP), then the updated water balance is limited to the PWP (lower limit). The contribution of upward water flux to soil water is not considered in this model. Details of the model description have been described by Mandal et al. (2002).

Daily rainfall data during the growing season of the crop was used as an input. Daily runoff was estimated from the daily rainfall data using the curve number (CN) techniques of the Soil Conservation Service (USDA, 1972) and combined with the soil water accounting procedure suggested by Sharpley and Williams (1990).

Root depth of the crop increases with time. The Borg and Grimes (1986) root growth model is used to determine the root depth:

$$\mathrm{RD} = \mathrm{RDM}\left[0.5 + 0.5\sin\left(3.03\frac{\mathrm{DAS}}{\mathrm{DTM}} - 1.47\right)\right] \quad (1)$$

where RD = root depth (cm) attained at any DAS, RDM = maximum root depth (cm) and DTM = DAS at maximum root depth. Maximum root depth of a sorghum crop is found to be more than 1 m but in the experimental fields there is impervious layer even below 30 cm soil depth, and soil depth of each block was considered as the maximum root depth for the crop for that block. In the model, evapotranspiration (ET) occurs at a maximum rate, called the potential evapotranspiration (PET), as long as soil water content in the root zone is more than a minimum threshold value (Doorenbos and Kassam, 1979). A term, the fraction of the total available soil water (p), i.e., the proportion of the total available soil water that can be depleted without causing ET to become less than PET, was introduced to define the minimum threshold value. The value of p depends on the crop, magnitude of PET, and the soil. Doorenbos and Kassam (1979) grouped crops according to the fraction to which the available soil water can be depleted while maintaining ET equal to PET. Sorghum has been defined as crop group 4. When the water content falls below the threshold value, the value of ET becomes a decreasing function of the water content and PET.

The value of PET is a function of crop type, crop growth stage, and climatic parameters. To obtain PET, the reference evapotranspiration (ET_0) is multiplied by the corresponding value of the crop coefficient (K_c) for the day. ET_0 (mm day^{-1}) was determined using the FAO Penman–Monteith equation (Allen et al., 1998). The K_c values of sorghum for initial (1–15 DAS), development (16–45 DAS), mid season (46–65 DAS), late season (66–90 DAS), and harvesting (91–105 DAS) stages were 0.4, 0.4–0.7, 0.7–1.0, 1.0–0.75 and 0.75–0.5, respectively (Doorenbos and Kassam, 1979). The values of K_c in mid season (K_{cmid}) and late season growth stages (K_{cend}) were modified according to local weather conditions and the crop height (Allen et al., 1998). The K_c values for each growth stage were converted into values for each day by interpolation.

2.2. Field experiment

A field experiment was conducted within a toposequence at Hayatnagar Research Farm (17°20′N latitude, 78°35′E longitude, and an elevation of 515 m above mean sea level) of Central Research Institute for Dryland Agriculture, Hyderabad, India, during 2001–2004. The climate is semi-arid with hot summers and mild winters. The mean maximum air temperature during summer (March, April and May) ranges from 35.6 to 38.6 °C. The mean minimum temperature during winter (December, January and February) ranges from 13.5 to 16.8 °C. The mean annual rainfall is 746.2 mm and accounts for approximately 42% of the annual potential evapotranspiration (1754 mm). Nearly 70% of the total precipitation is received during the southwest monsoon season (June to September).

The soil is a medium-textured, red soil (Typic Haplustalf as per USDA soil classification). In general, the slope varies between 1 and 3% with some divergent and complex slopes conducive to considerable erosion hazard. The surface soil has a low water holding capacity, is highly permeable and readily drains. The soil pH is neutral to slightly acidic. The study was conducted within a toposequence of 2 ha area. The hill slope was approximately 100 m wide by 200 m long, extending from a ridge top to the valley bottom and encompassed both convex (hydrologically divergent) and concave (hydrologically convergent) landform components. The study area was divided into six blocks, numbered sequentially down the hill slope (Fig. 1). Soil properties of the blocks are given in Table 1.

2.3. Testing of the soil water balance model

Daily weather data of rainfall, maximum and minimum temperatures, relative humidity, wind speed and solar radiation recorded in the observatory of the farm (400 m away from experiment area) was used for calculation. The sorghum variety CSH-9 was sown by a three-row tractor drawn planter with a row-to-row distance of 45 cm. The soil water content below 20 cm was measured with a neutron probe (model 4300 Troxler, USA), calibrated for the soil at the experimental site, at every 20 cm increment of soil depth down to a depth of 1 m. Four neutron probe access tubes were installed in each block. Water content of the top 20 cm soil layer was measured by a Theta probe (type ML2x, Delta T

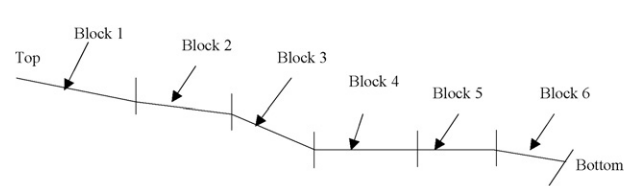

Fig. 1 – Layout of the blocks within the Alfisol toposequence.

Table 1 – Soil properties of different blocks of the toposequence

Block no.	Soil texture	Soil depth (cm)	Bulk density ($Mg\,m^{-3}$)	Soil water retention (w/w, %)	
				0.033 MPa	1.5 MPa
1	Sandy clay loam	30	1.51	9.22	4.59
2	Sandy clay loam	45	1.60	12.36	5.45
3	Sandy clay loam	43	1.59	12.19	6.81
4	Sandy clay	75	1.63	16.56	8.84
5	Sandy clay	75	1.60	15.09	8.22
6	Sandy clay	65	1.58	12.31	6.41

Devices, England). The FC, PWP, bulk density, and soil texture were determined using standard procedures (Klute, 1986).

The value of the soil water content in the root zone at the end of each day was modeled for the entire growing season (June to October) of the years 2001–2004. The predicted values for the daily soil water contents in the root zone during 2003 were compared with the observed values from the same soil depth in order to test the model. In block 6 one tipping bucket type runoff device was installed to monitor runoff and to compare the collected data with model output. The numbers of tips were monitored by a magnetic counter.

2.4. *Spectral reflectance measurements*

The canopy reflectance spectra were measured every week during the entire growing season of the sorghum using a portable spectroradiometer (LI-1800, LICOR) with remote cosine receptor (model 1800-11, LICOR) attached to a 1.5 m extension arm. The arm was held 1 m above the canopy. All the measurements were made near midday within 2 h solar noon. Incident and reflected solar radiations were measured by facing the remote cosine receptor towards the sky and the target, respectively. The measurements were taken over the wavelength range from 300 to 1100 nm at a scanning interval of 2 nm. Percentage reflectance values were calculated by dividing with the incident radiation. The values of spectral reflectance were averaged over the bandwidths 0.52–0.59, 0.62–0.68, and 0.77–0.86 μm to give values for the green (R_{green}), red (R_{red}), and near-infrared (R_{NIR}) bands of reflectance, respectively. The spectral bands were decided based on the LISS-IV multi-spectral camera used in the Indian Resourcesat-1 remote sensing satellite.

The following vegetation indices were used for the present experiment:

Simple ratio index (Rouse et al., 1974):

$$\text{simple ratio index} = \frac{R_{NIR}}{R_{red}} \tag{2}$$

Normalized difference vegetation index (NDVI) (Rouse et al., 1974):

$$\text{NDVI} = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}} \tag{3}$$

Green NDVI (GNDVI) (Gitelson et al., 1996):

$$\text{GNDVI} = \frac{R_{NIR} - R_{green}}{R_{NIR} + R_{green}} \tag{4}$$

Perpendicular vegetation index (PVI) (Jackson et al., 1980):

$$\text{PVI} = \frac{R_{NIR} - aR_{red} - b}{\sqrt{a^2 + 1}} \tag{5}$$

where 'b' and 'a' are the intercept and slope of the soil line determined by a linear regression of the reflectance ratios for the red and infrared bands taken over bare soil when the soil water conditions were dry to wet.

Soil adjusted vegetation index (SAVI) is defined by Huete (1988) as:

$$\text{SAVI} = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red} + L}(1 + L) \tag{6}$$

L is a constant used to minimize soil brightness influences for which Huete suggested a value of 0.5 for annual field crops; therefore this value was used in the present study.

A modified SAVI (MSAVI) that replaces the constant L in the SAVI equation with a variable L function is presented by Qi et al. (1994)

$$\text{MSAVI} = (1 + L)\frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red} + L}, \quad \text{where } L = 1 - 2a \times \text{NDVI} \times \text{WDVI} \tag{7}$$

in which the weighted differential vegetation index (WDVI) (Clevers and Verhoef, 1993) is given by:
$\text{WDVI} = R_{NIR} - (aR_{red})$

where 'a' is the slope of the soil line. L becomes smaller as the vegetation becomes more dense i.e., L varies with the canopy cover from 0 (very dense) to 1 (very sparse).

The spectral characteristics were measured by conducting another experiment on sorghum, taking a recommended fertilizer dose and zero fertilizer as treatments in 2003 in same toposequence. In fertilizer plots, recommended doses of 40 kg N ha^{-1} and 13 kg P ha^{-1} were applied. Half of the N and the entire P were applied at the time of sowing and remaining N was applied at 40 DAS. The leaf area was measured using a leaf area meter (LI-3100C area meter, LI-COR, USA). Yellow and dry leaves were excluded from the measurement. The plant samples were oven dried at 80 °C for 48 h and weighed for crop dry biomass ($g\,m^{-2}$). Sorghum was mechanically harvested during October and grain yield ($kg\,ha^{-1}$) was determined on plot basis.

2.5. Yield estimation

The values of the model output for AET, from sowing to harvesting, were used to evaluate the crop water deficit. The crop-growing season was divided into N growth stages ($i = 1, N$), which coincide with the vegetative, flowering, grain-formation and maturity stages of crop growth. Additive and multiplicative forms of water-production functions, using the AET and PET values, were then used to predict crop yield.The additive model: relative yield values

$$\frac{Y}{Y_m} = \left[1 - \sum_{i=1}^{N} K_i \left(1 - \frac{AET}{PET}\right)_i\right] \tag{8}$$

The multiplicative model: relative yield values

$$\frac{Y}{Y_m} = \prod_{i=1}^{N} \left[1 - K_i \left(1 - \frac{AET}{PET}\right)_i\right] \tag{9}$$

where Y = actual harvested yield, Y_m = maximum harvested yield obtained when water is not limiting (i.e., when AET = PET), and K_i = yield response factor for each phenological stage. The K_i for sorghum was 0.2, 0.55, 0.45, and 0.2 for the vegetative, flowering, yield formation, and ripening period, respectively (Doorenbos and Kassam, 1979).

A daily accumulative water stress index (WSI), weighted by phenological stage, was also used for assessment of grain yields. The WSI values are a daily integration of plant available soil water, evaporative demand, and plant phenological stage susceptibility, and are defined for the growing season as:

$$WSI = \sum_{i=1}^{N} \left(1 - \frac{AET}{PET}\right)_i K_i \tag{10}$$

The observed yield of sorghum was compared with the estimated yield obtained using the additive and multiplicative water-production functions, as well as with the WSI. A relationship was developed, using multiple regression analysis, taking yield as the dependent variable and spectral vegetation indices and either the water stress index or the relative yields calculated using either the additive or multiplicative water production function as independent variables.

2.6. Statistical analysis

For testing of the soil water balance model, a linear regression equation, $Y = c + mX$, was determined using X as the observed soil water values and Y as the soil water balance model outputs during the crop growth period in 2003. The values of c (the linear regression coefficient of the intercept), m (slope), r^2 (where r = the correlation coefficient), and standard error were calculated. Using this regression equation, predicted soil water contents were calculated for each day of model output during the crop growing season. The predicted soil water content value carries an error that must be considered in the comparison of modeled versus measured soil water values. A 95% confidence interval for the predicted soil water was constructed using the mean square error (MSE) of the regression (Gomez and Gomez, 1984)

$$MSE = \frac{\sum y^2 - (\sum xy)^2 / \sum x^2}{n - 2} \tag{11}$$

where n is the number of observations, x and y are the deviations from the mean of the dependent (observed) and the independent variable (model), respectively. The 95% confidence interval is computed as:

$$C.I.\,(95\%) = m \pm t_{0.05} \sqrt{\frac{MSE}{\sum x^2}} \tag{12}$$

$t_{0.05}$ is the tabulated t value (from the statistical t-distribution), at the 5% level of significance with ($n - 2$) degrees of freedom. The upper and lower boundaries of the confidence interval were drawn for each day predicted soil water content values.

Pearson correlation coefficients were used to study the relationship between spectral vegetation indices and biological variables. Multiple regressions were performed using yields from 2001 to 2003 as the dependent variable and the spectral vegetation index and, either the water stress index or the additive or the multiplicative water production functions, as independent variables. The multiple regression equation was tested with the estimated vis-à-vis with the observed yields for 2004.

3. Results and discussion

3.1. Testing of soil water balance model

Comparison between the observed and simulated values of the soil water content of the active root zone under the sorghum crop during 2003 for the different blocks of the Alfisol toposequence, revealed a close similarity (Fig. 2). Upper and lower 95% confidence intervals are plotted around the predicted soil water based on the error involved in estimating the 'c' and 'm' parameters (Table 2). Observed values for all six blocks are within the limits of the 95% confidence interval. Also, the high r^2 value (>0.70), and its level of significance at $P < 0.001$, for all blocks indicated good agreement between modeled and observed values for the estimation of root zone soil water content.

The pattern of fluctuation of the soil water content values throughout the growing season remained similar for both observed and simulated cases for all blocks. During the periods when there was an absence of rainfall, a gradual depletion in soil water content in the root zone was observed. Immediately following a rainfall event, depending upon the amount of rainwater involved, the depletion of soil water from the root zone would be predominantly due to downward flux, into the "passive" layer and then, to the deeper soil layers as deep percolation. Following this initial redistribution of soil water, the predominant process by which soil water was depleted would be due to evapotranspiration as the plants took up water. Conversely, whenever there was any rainfall during the crop-growing season, the soil water content in the root zone was observed to increase in both the measured and predicted cases.

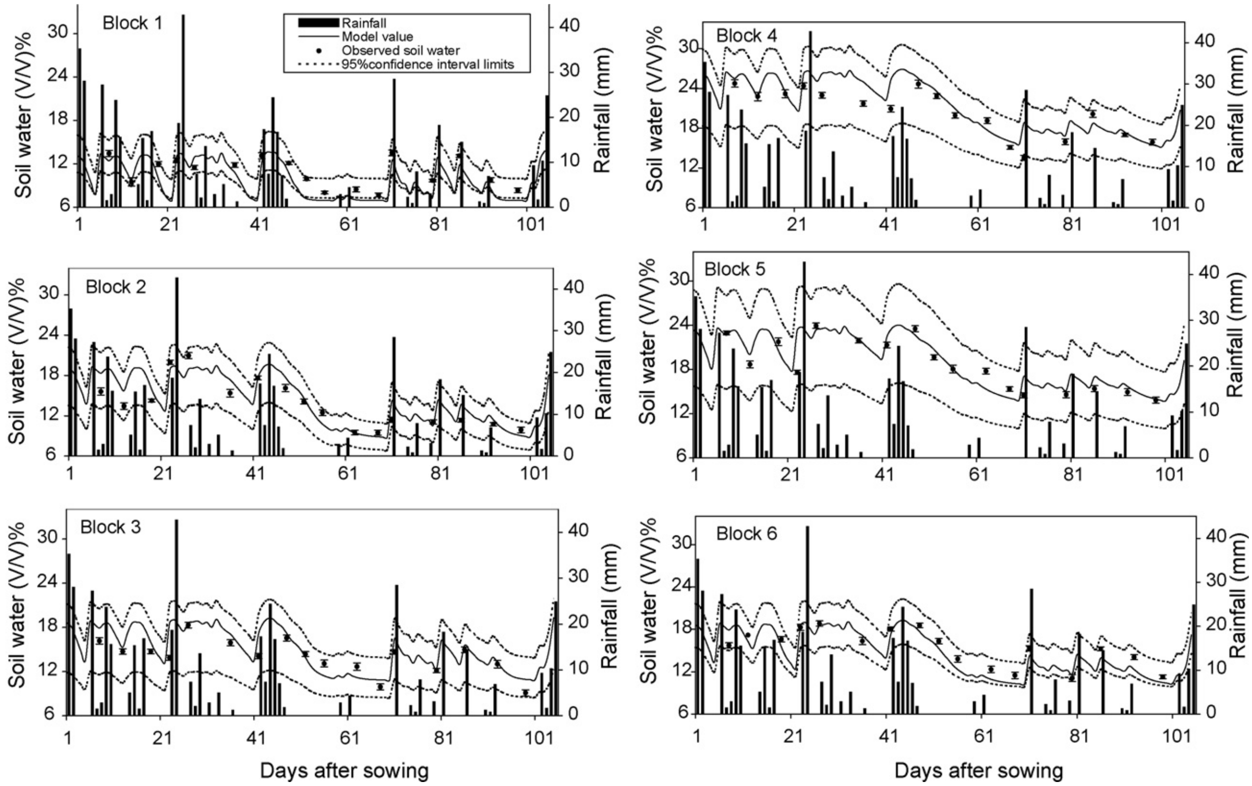

Fig. 2 – Observed and model output of soil water content during the growth period of sorghum in each block of the topesequence. Upper and lower 95% confidence intervals are also constructed around the model prediction (error bars are ±1S.D.).

Although the total rainfall (476.2 mm) during the crop growing season of 2003 was more than the total PET requirement (308.6 mm), the crop still suffered water stress since there was also a considerable amount of water that was lost from the field as runoff or that percolated below the root zone. Block 1 was the hilltop of the landscape and had comparatively light textured soil with the lowest water retention capacity of the six blocks (Table 1). For block 1, out of 17 observations, 14 differed by less than ±2% in soil water content from the model output (Fig. 2). For the other three cases, the observed values were 2.03, 2.38 and 2.74% higher in soil water content than the model predictions. The model output showed 6% of total rainfall was lost as runoff from block 1 during crop growing season. However, high permeability and shallowness of the soil in that block resulted in the highest amount of percolating soil water (52.5% of rainfall) below the root zone. In the entire growing season, the crop in block 1 suffered water stress for 31 out of the 105 days when AET was less than PET. The soil water content was at PWP for 11 days of the growing period.

In block 2, all observed values were within ±2.75% of the soil water content values of the model output. Predicted runoff and percolation below the root zone were 27.9 and 211.6 mm, respectively, for block 2. In this block, crops suffered water stress for 26 days during the entire crop growth period. Block 2 was at a relatively lower elevation than block 1 and the soil was deeper (Table 1). Soil in this block also had higher water retention capacity, and, therefore, crops suffered relatively less from water stress than in block 1.

Block 3 was located below blocks 1 and 2 in the landscape but it had a hydrologically divergent convex slope and the

Table 2 – Validation of model performance in respect to observed and model output of soil water including the intercept and slope parameters used to predict soil water

Block no.	c (intercept)	*m* (slope)	r^2	Standard error (%, v/v)	P-value
1	3.293	0.769	0.824	0.881	<0.001
2	1.216	0.875	0.817	1.545	<0.001
3	3.755	0.687	0.696	1.303	<0.001
4	3.039	0.805	0.801	1.628	<0.001
5	1.953	0.871	0.744	1.823	<0.001
6	3.060	0.832	0.884	0.915	<0.001

Table 3 – Observed and model output (predicted) runoff values for block 6 during 2003 crop growth period

DAS	Rainfall (mm)	Rain in previous day (mm)	Predicted runoff (mm)	Observed runoff (mm)
1	35.2	7.2	5.82	4.30
2	28.0	35.2	6.15	7.11
9	23.7	2.8	2.77	3.87
10	15.5	23.7	0.64	0.89
15	15.3	5.0	0.05	0.11
17	16.8	1.4	0.26	0.54
24	42.7	18.6	11.20	10.40
44	24.3	7.3	2.20	2.50
45	16.6	24.3	0.49	1.50

slope gradient was also more than 2%. The crop suffered water stress for 26 days in block 3.

Out of the six blocks, blocks 4 and 5 retained the highest amount of soil water (Fig. 2). Values predicted by the model also confirmed this. Soil in blocks 4 and 5 had a comparatively finer texture with higher water retention capacity than soil in the other blocks. Soil depth is also relatively higher in these two blocks than in the other four blocks. Moreover, both of these blocks had concave slopes and the slope gradient was less than one percent. A similar observation was also noted by Chamran et al. (2002) when a simple, one-dimensional model was used for estimating water storage on a hillslope. The predicted runoff for blocks 4 and 5 were 33.4 and 208.6 mm, respectively, while the corresponding predicted percolation below the root zone was 37.6 and 208.7 mm, respectively. These two blocks generated higher runoff than the other blocks as runoff mostly depended on antecedent soil water rather than water retention capacity of soil. In blocks 4 and 5, the crop suffered water stress for 23 and 25 days, respectively.

Runoff from block 6 was actually measured and compared with predicted values (Table 3). The high r^2 value (0.951, significant at $P < 0.001$) with low standard error (0.81) indicates good agreement between model output of runoff and observed runoff. Here, the curve number (CN) techniques of the Soil Conservation Services were used with a daily time step in order to predict daily runoff for a specific precipitation event on a daily basis. The SWRRB (Arnold et al., 1990) and SWAT (Arnold et al., 1996) model also used CN techniques to estimate daily runoff from daily rainfall data. Also, Panigrahi and Panda (2003) used the CN techniques of Soil Conservation Service in a simple soil water balance model to simulate soil water content in the active root zone of a mustard crop and that model satisfactorily simulated the soil water content in the active root zone of the crop on a daily basis.

Although all the observed values of soil water were within the 95% confidence interval of the model output for all the blocks, there were some cases where discrepancies between the observed and simulated soil water content were noticeable. Discrepancies can occur because of the limitations of both the model and of the method by which soil water content was measured. The assumption of instantaneous, uniform redistribution of soil water throughout the effective root zone is no doubt a limiting assumption of the model on a field scale. This assumption is justified in terms of simplicity of the model and in view of slow rate of ET. The neutron probe was used to get the observed soil water. The accuracy of a neutron probe in estimating soil water content is usually affected by many factors including the length of count interval, probe calibration and spatial heterogeneity of the soil water (George et al., 2000). Also, various constituents of soil other than water produce a cumulative effect on the count rate and probe calibration. The limitation of using neutron probe may also add to the deviation between observed and model output.

3.2. *Crop growth and spectral characteristics*

A soil line was drawn (Fig. 3) using the spectral reflectance in the red and infrared bands for different levels of soil water content in the experimental field. Six vegetation indices, i.e., the simple ratio of red and infrared bands, NDVI, green NDVI, PVI, SAVI, and MSAVI were analyzed for the entire crop growth period. All six vegetation indices increased with an increase in crop growth, until reaching a maximum value during the booting to anthesis stage of crop development, and then decreased as the crop approached towards senescence. Generally, after the 7th week from sowing, reflectance in the near infrared region reached the highest value of the season, while reflectance in the visible portion reached the lowest value. At later stages, after the 12th week from sowing, yellowing and wilting of the plants gradually became apparent. Therefore, the reflectance in the visible region increased as a result of decreasing chlorophyll concentration while the reflectance in the near infrared region decreased due to wilting and the subsequent

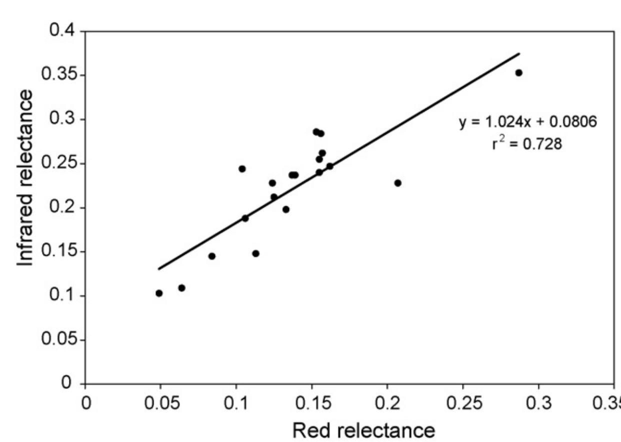

Fig. 3 – Soil line using spectral reflectance from bare soil in red and infrared band under different levels of soil water contents in the experimental field.

Table 4 – Pearson correlation coefficients for the relationship between sorghum crop dry mass, leaf area index (LAI), yield and the spectral vegetation indices at different growth stages during 2003

Vegetation index	Days after sowing								
	28 (tillering[a])	35 (tillering[a])	43 (late vegetative[a])	50 (booting[a])	57 (heading[a])	64 (anthesis[a])	72 (milk grain[a])	81 (maturity[a])	94 (late maturity[a])
LAI									
Simple ratio	0.328	0.358	0.541*	0.651**	0.709**	0.685**	0.500*	0.296	0.089
NDVI	0.316	0.344	0.553*	0.634**	0.648**	0.707**	0.502*	0.308	0.093
GNDVI	0.212	0.262	0.503*	0.661**	0.473	0.565*	0.357	0.187	0.124
SAVI	0.262	0.251	0.429	0.675**	0.630**	0.676**	0.485	0.211	0.203
MSAVI	0.333	0.309	0.489	0.657**	0.681**	0.693**	0.525*	0.263	0.246
PVI	0.095	0.251	0.396	0.529*	0.457	0.300	0.211	0.006	0.190
Dry biomass									
Simple ratio	0.357	0.321	0.391	0.521*	0.418	0.389	0.473	0.140	0.175
NDVI	0.381	0.393	0.421	0.391	0.418	0.389	0.473	0.140	0.175
GNDVI	0.229	0.281	0.299	0.541*	0.511*	0.411	0.300	−0.102	−0.890
SAVI	0.350	0.410	0.497*	0.534*	0.519*	0.436	0.330	0.284	0.136
MSAVI	0.257	0.422	0.516*	0.587*	0.516*	0.546*	0.435	0.423	0.199
PVI	0.141	0.212	0.365	0.316	0.429	0.436	0.199	0.109	0.064
Yield									
Simple ratio	0.204	0.292	0.444	0.512*	0.524*	0.576*	0.504*	0.294	0.163
NDVI	0.231	0.214	0.424	0.511*	0.542*	0.616**	0.501*	0.317	0.187
GNDVI	0.108	0.302	0.497*	0.438	0.521*	0.563*	0.437	0.224	0.079
SAVI	0.205	0.394	0.575*	0.520*	0.544*	0.656**	0.419	0.256	0.211
MSAVI	0.243	0.396	0.596*	0.561*	0.636**	0.701**	0.584*	0.220	0.117
PVI	0.141	0.271	0.133	0.421	0.363	0.381	0.317	0.179	0.022

* and ** denote significance at the 0.05 and 0.01 probability levels, respectively.
[a] Growth stages.

Table 5 – Mean values (±S.D.) for crop dry biomass (g m^{-2}), leaf area index (LAI), and vegetation spectral indices measured for sorghum during 2001–2003 at booting to milk-grain stages

Index	Stages of growth			
	Booting	Heading	Anthesis	Milk-grain
LAI	2.612 (0.49)	2.574 (0.44)	2.356 (0.42)	2.213 (0.33)
Dry biomass	749 (102)	1087 (155)	1127 (146)	1227 (122)
Simple ratio	7.425 (1.52)	7.599 (1.63)	7.291 (1.44)	7.012 (1.47)
NDVI	0.753 (0.04)	0.767 (0.05)	0.759 (0.03)	0.750 (0.03)
GNDVI	0.742 (0.04)	0.734 (0.03)	0.683 (0.02)	0.628 (0.03)
SAVI	0.577 (0.03)	0.609 (0.03)	0.636 (0.04)	0.556 (0.03)
MSAVI	0.598 (0.03)	0.658 (0.03)	0.667 (0.04)	0.561 (0.04)
PVI	0.268 (0.04)	0.361 (0.04)	0.268 (0.05)	0.251 (0.04)

exposure of the soil background. Similar trends were also noticed when the spectral vegetation indices were measured for durum wheat (Aparicio et al., 2000) and for rice (Chang et al., 2005) for predicting yields. Crop dry matter continues to increase until the grain filling stage. Subsequently, there is an overall decrease in dry biomass due to losses in vegetative dry mass accompanying the onset of plant senescence and the increase in grain mass. Maximum LAI was recorded at the booting stage of crop growth. Thereafter, LAI decreased progressively until maturity. Data recorded during 2003, in both the applied fertilizer and no fertilizer treatments, was used in order to study the relationship between spectral indices and the crop growth parameters. Significant ($P < 0.05$) positive correlations between the various vegetation indices and both LAI and yield, were observed between 50 and 72 DAS (Table 4). The Pearson correlation coefficients were relatively less for the dry biomass relationship with the spectral indices, than for the yield and LAI with those indices. The sorghum crop proceeds through four vegetative stages (i.e., booting, heading, anthesis, and milk-grain) during 50–72 DAS. PVI was not significantly correlated with any crop growth parameter, including yield, except at the booting stage, with LAI. This may be that PVI is still significantly affected by the soil (Huete, 1988). The Pearson coefficients of correlation were highest for the heading to anthesis stages.

The mean values, for the entire toposequence, of all the vegetation indices, as well as the crop dry biomass and the LAI, for sorghum grown between 2001 and 2003 at booting to milk-grain stages under recommended fertilizer doses are presented in Table 5. The highest values for the simple ratio and for NDVI were observed during the heading stage of the crop. The GNDVI was highest during the booting stage. Maximum SAVI as well as MSAVI were recorded during the anthesis stage. Among all the vegetation indices, MSAVI showed highest average correlation coefficients between booting to milk-grain stages with dry biomass, LAI and yield.

3.3. *Estimation of yields using spectral indices and actual evapotranspiration*

The grain yield of sorghum was recorded during 2001–2003 (Table 6). A maximum yield of 2.6 t ha^{-1} was recorded, during 2002, in block 4. The lower yields in 2003, affecting the entire toposequence, may have been because of delayed sowing and a minor infestation of grain mold during the harvesting stage of the crop. The grain yield was comparatively higher from blocks 4 and 5 than from the other blocks because of higher soil depth as well as the higher available water capacity of the soil in these two blocks. Block 2 recorded the third highest average yield because of its higher available water capacity and a lower slope gradient (<2%). The lowest average yield was noted in block 1 because of its shallow soil depth (30 cm) and the lower available water holding capacity of its soil. Toposequence related yield variability has also been reported for pearl millet in the Sahelian region (Rockstrom et al., 1999).

Actual evapotranspiration calculated by the water balance model was used for estimation of the yields. The maximum yield for the experimental site was taken to be 3.097 t ha^{-1} and was calculated from the average of the three highest sorghum grain yields recorded during the last 15 years of cultivation in the toposequence. This maximum yield value of 3.097 t ha^{-1} was then used to estimate the yield for all the blocks during 2001–2003. As with the observed yields, the additive and multiplicative models gave higher relative yield values for blocks 4 and 5 than for the other blocks. The root zone soil water budget model gave a similar trend of estimates of grain yields as a function of soil depth and available water holding capacity like observed yields. Though there was a good relationship between relative yield values for both the additive model ($r^2 = 0.61$, significant at $P < 0.001$) and the multiplicative model ($r^2 = 0.63$, significant at $P < 0.001$), the deviation from the estimated yield was −2 to 103% for the additive model and 7–119% for the multiplicative water production function (Table 6). The use of the maximum yield for estimation of yield predictions is very critical for getting effective results when using the water production function. The few unexpected maximum yields may have been obtained because of good seasonal rainfall distributions or crop varietal intervention but this maximum yield value does has very high weight-age in predicting the yield.

A water stress index was also used for estimating yield. The maximum water stresses occurred in block 1 (11.11–10.49) in all 3 years from 2001 to 2003 because of the shallow soil and low available water holding capacity. Conversely, the minimum water stresses, ranging from 1.53 to 3.82, were noted for blocks 4 and 5, during 2001–2003. A regression equation ($r^2 = 0.416$, significant at $P = 0.004$) was obtained for the relationship between the observed yields and the water stress index (Fig. 4). Nevertheless, deviation between

Table 6 – Observed and estimated yields of sorghum predicted by using additive, multiplicative water production function as well as water stress index and the percent deviation between observed and estimated yield during 2001–2003

Year	Block no.	Observed yield (t ha^{-1})	Relative yield values		Water stress index	Estimated yield (t ha^{-1})			Percent deviation		
			Additive model	Multiplicative model		Additive model	Multiplicative model	Water stress index	Additive model	Multiplicative model	Water stress index
2001	1	1.237	0.564	0.603	11.110	1.747	1.867	1.034	41.2	50.9	16.4
	2	1.665	0.778	0.784	5.752	2.409	2.428	1.562	44.7	45.8	6.2
	3	1.368	0.680	0.699	8.172	2.106	2.165	1.324	53.9	58.2	3.2
	4	1.744	0.945	0.946	1.994	2.927	2.930	1.932	67.8	67.9	−10.8
	5	1.500	0.910	0.912	2.826	2.818	2.824	1.850	87.9	88.3	−23.4
	6	1.554	0.799	0.805	5.538	2.475	2.493	1.583	59.2	60.4	−1.9
2002	1	1.835	0.577	0.637	10.488	1.787	1.973	1.096	−2.6	7.5	40.3
	2	2.209	0.945	0.945	2.002	2.927	2.927	1.931	32.5	32.5	12.6
	3	2.019	0.882	0.886	3.788	2.732	2.744	1.756	35.3	35.9	13.1
	4	2.628	0.957	0.957	1.533	2.964	2.964	1.978	12.8	12.8	24.7
	5	2.265	0.951	0.951	1.798	2.945	2.945	1.952	30.0	30.0	13.8
	6	2.128	0.940	0.941	2.229	2.911	2.914	1.909	36.8	36.9	10.3
2003	1	1.054	0.380	0.483	10.880	1.177	1.496	1.057	11.7	41.9	−0.3
	2	0.914	0.601	0.647	6.821	1.861	2.004	1.457	103.6	119.2	−59.4
	3	0.902	0.526	0.587	8.160	1.629	1.818	1.325	80.6	101.5	−46.9
	4	1.594	0.829	0.838	2.862	2.567	2.595	1.847	61.1	62.8	−15.9
	5	1.230	0.772	0.788	3.818	2.391	2.440	1.753	94.4	98.4	−42.5
	6	1.016	0.633	0.673	6.240	1.960	2.084	1.514	92.9	105.1	−49.0

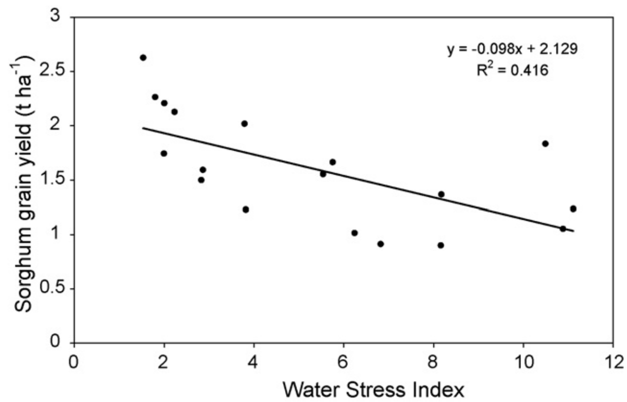

Fig. 4 – Water stress index and sorghum grain yield relationship during 2001–2003 in the toposequence.

observed and expected yields varied between −59.4 and 40.3%.

An attempt was made to use the relative water production function from both the multiplicative and additive models, as well as the water stress index, and the MSAVI recorded from the booting to the milk-grain stage, for estimating yields based on the yields observed during 2001–2003. The coefficients of determination for all combinations of regression (Table 7) were statistically significant, at least at the 1% level of significance. The relative yield values obtained using the multiplicative water production function with the MSAVI recorded during the heading stage gave the highest coefficient of determination ($P < 0.001$).

The multiple regression equation:

$$Y\,(\text{estimated yield}) = (2.586 \times \text{MSAVI(heading stage)}) + (1.94 \times \text{relative yield value using multiplicative water production function}) - 1.424$$

was used for estimating the yield for 2004. The percent deviation between observed and estimated yields varied between −9.5 and 8.5 ($r^2 = 0.949$, $P = 0.001$) (Table 8). Combining the spectral characteristics with the water production function calculated from the water balance model gave a better estimation of yield than if either of the two factors had been used separately. The spectral characteristics of crop might tell the better picture of above ground of crop and water production function could explain below the soil surface. Therefore, using both indicators gave a better estimate of the yield. The estimation of yield using the water production function alone is effective only when water is the single limiting factor for crop development. However, the plants also suffer from nutritional deficiency as well as from pests, diseases, and weeds. The recommended dose of fertilizer is generally decided upon, not only on the basis of plant uptake of the nutrients but also, by taking into account the risks associated with rainfed cultivation. The recommended dose of fertilizer was as low as 40 kg ha^{-1} N in this region. In a year with a good seasonal distribution of rainfall, the yield may be restricted due to too low dose of fertilizer. This deficiency may be detected in the spectral signature. Similarly, poor crop development due to pests, diseases, and weeds may also be apparent in the spectral signature.

Table 7 – Coefficients of determination from multiple regressions using yield during 2001–2003 as the dependent variable and MSAVI, and relative yield values from both the additive and multiplicative models, and the water stress index as independent variables

Spectral vegetation index	Growth stage	Relative yield values		Water stress index
		Multiplicative water production function	Additive water production function	
MSAVI	Booting	0.678 ($P < 0.001$)	0.643 ($P < 0.001$)	0.479 ($P = 0.008$)
MSAVI	Heading	0.682 ($P < 0.001$)	0.673 ($P < 0.001$)	0.556($P = 0.002$)
MVASI	Anthesis	0.641 ($P < 0.001$)	0.624 ($P = 0.001$)	0.499 ($P = 0.006$)
MVASI	Milk-grain	0.643 ($P < 0.001$)	0.625 ($P = 0.001$)	0.462 ($P = 0.01$)

Values in the parentheses are the significant levels of probability.

Table 8 – Observed and estimated yields of sorghum for 2004 using the regression equation Y (estimated yield) = 2.586 × MSAVI (heading stage) + 1.94 × relative yield values using multiplicative water production function − 1.424

Different block	Observed yield (t ha^{-1})	Relative yield values using multiplicative water production function	MSAVI (heading stage)	Estimated yield (t ha^{-1})	Percent deviation
Block 1	1.188	0.420	0.647	1.076	9.43
Block 2	1.430	0.570	0.672	1.431	−0.11
Block 3	1.067	0.524	0.561	1.055	1.09
Block 4	1.540	0.714	0.643	1.636	−6.23
Block 5	1.600	0.679	0.691	1.692	−5.76
Block 6	1.340	0.587	0.588	1.247	6.91

4. Conclusion

A two-layer simple water balance model was used for estimating soil water and runoff within a toposequence of varying soil depth and available soil water holding capacity. Although all the observed values of soil water in root zone were within the 95% confidence interval and there was high r^2 (>0.70, significant at $P < 0.001$) between observed and model values of soil water, variations were noted in a few cases. This may be due to the assumption of instantaneous, uniform redistribution of soil water over the effective root zone in the model, as well as being due to errors associated with the use of neutron probe for recording observed soil water value. The spectral vegetation indices, namely the simple ratio, normalized difference vegetation index (NDVI), green NDVI, perpendicular vegetation index, soil adjusted vegetation index (SAVI) and modified SAVI (MSAVI), were also recorded throughout the growth period of the sorghum crop. Those vegetation indices measured during the booting to anthesis stages were positively correlated ($P < 0.05$) with both leaf area index and yield. The correlation coefficient was relatively smaller for dry biomass than for LAI and yield when related to the spectral indices. The MSAVI, measured during the booting to milk-grain stage, gave the highest positive correlation when related to yield which may be because of a lower soil background influence for that index when compared with the other indices. Variations between observed and predicted values were observed when the water budget model was used for estimating grain yields as a function of soil depth and available water holding capacity. However, the yield estimation was improved when spectral vegetation indices, measured during the booting to milk-grain stages, were combined with the soil water balance model. The water balance model has a scope of real time assessment of soil water having varying soil type. The yield map, developed in this study will not only be useful for depicting spatial variability within the field but will also help in site-specific management decisions, particularly in irrigation and fertilizer application.

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