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Research paper

Utilization of Water Budget Model for the Design of Water Harvesting to Increase Sorghum Yield in Gadaref Mechanized Rain fed Areas-Sudan

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ABSTRACT

Gadaref State is one of the major areas that depend on rain-fed agriculture. The main objective of the study was to employ Budget Program to determine the size of rainfall catchments area required to improve Sorghum crop yield in the rain-fed areas of Gadaref, Sudan using water balance (BUDGET) to postulate crop plantation on the computer via exploiting records of the climatologically data of the area for a period of 30 years (1980 - 2009) in addition to the soil and crop data. Evapotranspiration for the crop has been calculated using ETo program. Penman Montieth (FAO) equation, and RAINBO program was used to calculate the probability of rains using the normal distribution. The years were classified according to rain quantities to very wet, wet, normal, dry and very dry years. The monthly rain, minimum and maximum temperature, evaporation, mean wind speed and the mean sun rays were the climatologically data used. The study compared estimated productivity to the actual one and provided the shortage in water quantity for the blank (water stress) and surface runoff and by using these values to calculate the percentage of water catchments areas to the cultivated areas. By using the probability 67% and efficiency factor range between 0.5 to 0.75 as recommended by FAO, the percentage was 3.16:1 to 2.12:1 to each efficiency factor, respectively. And when the efficiency coefficient calculated from the rain quality and evaporation for each year the efficiency factor was found to be 0.74 and C:CA percentage was 2.18:1. By using the probability 67% and the medium value for the water stress the percentage C:CA was 3.8:1. The reservoir capacity is 927 m^3/fed.

***Keywords*:** Catchments area, cultivated area, sorghum, mechanized rain-fed, water harvesting, water stress.

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استخدام برنامج الموازنة المائية لتصميم حصاد المياه لزيادة إنتاجية الذرة الرفيعة في القطاع المطري الآلي بالقضارف- السودان

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ولاية القضارف تعتبر من اكبر مناطق الزراعة المطرية بالسودان. الهدف الرئيسي من الدراسة هو تطبيق برنامج الموازنة المائية لتحديد مساحة منطقة تجميع مياه الأمطار Catchment area التي نحتاجها لتحسين إنتاجية محصول الذرة الرفيعة. تم استخدام برنامج الموازنة المائية (BUDGET) لمماثلة زراعة المحصول في الحاسب الآلي باستخدام بيانات المناخ لفترة 30 سنة (1980 ـ 2009) بالإضافة إلي بيانات التربة والمحصول. تم حساب تبخر– نتح المحصول باستخدام برنامج (ETo) باستخدام معادلة بنمن- مونتيث المعدلة من قبل منظمة الاغذية والزراعة FAO واستخدام برنامج رينبو لحساب احتمالية نزول المطر باستخدام التوزيع الطبيعي للأمطار ، وتم تقسيم فترة السنوات إلي سنوات رطبة جداً، سنوات رطبة، سنوات طبيعية، سنوات جافة وسنوات جافة جداً. والبيانات المناخية المستخدمة هي الأمطار الشهرية ، اعلي وادني درجة حرارة، التبخر، متوسط سرعة الرياح ومتوسط ساعات الإشعاع الشمسي. قارنت الدراسة بين التقديرات الإنتاجية للبرنامج والإنتاجية الحقيقية وحددت القصور في كمية مياه الري (الشد الرطوبي) وكمية الجريان السطحي من مياه الأمطار وباستخدام هذه القيم تم حساب نسبة مساحة منطقة تجميع المياه إلي المساحة المزروعة. عند استخدام احتمالية 67% ومعامل كفاءة يتراوح بين 0.5 إلي 0.75 (موصي بها من FAO) وجد أن النسبة لـC/CA تتراوح بين 3.16:1 و 2.12:1 لكل معامل كفاءة علي التوالي. وعند حساب معامل الكفاءة من كمية الأمطار والتبخر لكل سنة وجد أن قيمته تساوي 0.74 وأصبحت نسبة الـ C/CA تساوي 2.18:1 وباستخدام احتمالية 67% ومتوسط قيمة الشد الرطوبي أصبحت نسبة الـ C/CA 3.8:1 والسعة التخزينية لمنطقة التجميع تساوي 927م^3/ فدان.

Introduction

Sudan comprises about 1861484 km^2 (718722 square miles) making it the third largest country in Africa. Extending over different climatic zones from the desert zone (0-100 mm rain) in the North to the humid zones (800-1600 mm rain) in the South. Out of this area, 87 million ha are arable cultivated land (Buraymah, 2000). From the total cultivated land, rain-fed agriculture occupies about 15 million ha; of which 9 million ha are in the traditional agriculture (TA) while the remaining in the mechanized agriculture (MA). Sorghum (*Sorghum bicolor*) is the main staple food crop in Sudan representing 80% by weight of the cereal crops grown in the country in both 2004 and 2005 (FAO/WFP, 2006). It is a well-adapted crop for central Sudan and is grown extensively under irrigated and dry land conditions. Sudan is self-sufficient in sorghum production and is able to export some, in years of good production.

The crops yield under the dry land/rain-fed conditions depends on the interaction between soil, water, plant and atmosphere as a continuum system. Dry land farming frequently suffers crop water stress (i.e. deficit of plant accessible soil water). Actual crop water stress depends on rainfall partitioning, the water holding capacity of the soil, and antecedent soil water content. It also depends on crop water demands and water uptake capacity. To quantify the impacts of all the variables it is required at least to employ simple water balance analysis (Barron *et al*., 2003). Crop growth and yield as influenced by various environmental parameters (different conditions of water supply) have been simulated and modeled by several computer algorithms (CROPWAT, BUDGET, RAINBO, DSSAT, APSIM, ETo, and EPIC). The general assumption postulated by many scholars is to use simulation models to estimate potential yield in new areas; crop behaviors under different conditions of water supply to forecast yield before harvest, to estimate sensitivity of crop production, to climate change, to compare management options, technology level and performance of varieties (Williams *et al*., 1989; McCaw *et al*., 1996 and Jones *et al*., 1998). Although various algorithms can achieve such objective in reality, such assumption is not frequently tested. Simple water harvesting techniques were often considered as an attractive option to increase sorghum yields and help the local people to attain more revenue and reduce their mass immigration towards large cities.

There are two major forms of water harvesting; in-situ or within-field water harvesting (ISWH) and external water harvesting (EWH). In ISWH, rainwater is collected where it falls to be used more efficiently on the same surface (often referred to as water conservation). In EWH, water is collected on one surface to be applied on another and often referred to as runoff farming/collection and storage (Falkenmark *et al.*, 2001). ISWH techniques include activities such as mulching, deep tillage, contour farming and ridging. The purpose behind these methods is to ensure that the rain water is held long enough on the cropped area to ensure infiltration (Habitu and Mahoo, 1999). Ridge tillage has been defined as "a method of land preparation whereby the top soil is scraped and concentrated in a defined region to deliberately raise the seedbed above the natural terrain" (Lal, 1990). Crops usually grown on the ridges in rows, with one or more rows per ridge, even though in some cases crops may be grown in the furrows to make advantage of the wetter condition of the soil under the furrow. It is an effective water management, erosion control practice when the system is established in the contour (contour ridge), and the slope of the land is less than 7 percent (Moldenhauer and Onstad, 1977). Ridge tillage is very effective in conserving water in the root zone in semi-arid to sub-humid regions, particularly when ridges have cross ties in the furrows recognized either as tied-ridging, furrow blocking or basin tillage (Gardner *et al*., 1999). In clay soil, tied-ridging is likely to reduce surface runoff and increase retained water within the field if carefully designed across the slope. Past and recent research works in Africa has shown that tied ridging often leads to little or no runoff. Similar results also obtained in the USA (Krishna, 1989).

In addition to water harvesting technique, the use of conservation tillage measures, such as minimum tillage and no-tillage, has been tested in some developing countries to conserve soil water (Rosegrant *et al*., 2002). No-tillage is a method of crop production that involves no seedbed preparation other than opening the soil for placing seed at the desired depth. Adequate quantities of residues are often required to remain above the soil surface to provide cover and to protect the soil against erosion until the canopy of the next crop is well-developed (Gardner *et al.*, 1999). The catchments: cultivated area ratio can be estimated as (FAO, 1991):

$$\frac{\text{Catchments area}}{\text{Cultivated area}} = \frac{\text{crop water requirement} - \text{design rainfall}}{\text{design rainfall} \times \text{runoff coeff.} \times \text{eff. factor}}$$

Runoff coefficient is the proportion of rainfall, which flows over the ground as surface runoff. Efficiency factor is the factor that takes into account the inefficiency of uneven distribution of the water within the field as well as losses due to evaporation and deep percolation. It normally ranges between 0.5 and 0.75 (FAO, 1991). In recent years, the yield and productivity of sorghum have been declining drastically. The causes may be due to the lack of appropriate soil and water management practices.

One of the practices made in the rain fed sector to alleviate this problem relies on delayed seeding of sorghum crop as a weed control measure. Determination of the length of growing season for rain fed farming system in a certain climatic zone starts by the onset of adequate rainfall that can satisfy at least half of the amount of evapotranspiration. As such, late sowing results in short growing period and thereby reduced the crop yields. However, the optimum time to satisfy crop water demand need to be determined via accurate, practical and user-friendly water balance model. As given before, to achieve this target the available models are hardly used. Due to the spatial and temporal variability of rainfall, it is necessary to supplement rainwater by irrigation water from permanent sources or to harvest and store the excess rainwater to satisfy the crop water need in the time of water deficit.

This study selected sorghum crop, due to its importance, as a focal to employ Budget Program to determine the size of rainfall catchments area required to improve sorghum crop yield in the rain fed areas of Gadaref, Sudan.

Materials and Methods

Location: Gadaref State extends between latitudes 12º 40″ and 15º 45″ N and longitudes 33º 34″ and 37º 10″ E over 75263 km2. Its elevation is about 600 meters above sea level, and lies between major tributaries of Blue Nile, Rahad and Atbara Rivers.

Climate: Rainfall varies from South to North and most of the rain falls in summer in the period between May to October, when the unstable air of equatorial origin reaches for northward. The climatic zones are classified into arid zone (200-400mm rain fall), semi- arid zone (400-600 mm rainfall) and the dry monsoon zone (600-800 mm rainfall) (Vander Kevie 1973; Buraymah, 2000). The temperature is high in summer (40ºC) and warm in winter (15ºC). The relative humidity varies between 24% in April and 73% in August.

Land use: Gadaref State lies in the central clay plain of Sudan. Its southern part, which lies south of 400 mm rain line, is the most productive and economically important area in Sudan. Since 1940's it is leading the States in mechanized rain- fed agriculture where about 3 million ha are under mechanized farming system (Farah and Jnanaga, 1996). Rain-fed mechanized farming is the major land use system in the state. Other occupations include irrigated agriculture (Rahad Scheme and wild flooding around Atbara and Rahad Rivers) and semi nomadic pastoralists herding cattle, camels, sheep and goats in Botana area.

Data collection: The data collected included the following:

Meteorological data: The mean monthly data of maximum and minimum temperatures, rainfall, relative humidity, wind speed, bright sunshine hours and evaporation from Gadaref Meteorological station for the period of 30 years (1980-2009).

Soil data: Meheissi (1998) described the soil of the area, given in Table (1), as dark brown moist and dry, clay, weak to moderate coarse prismatic structures breaking into coarse and medium angular and sub angular blocky structure, very hard when dry and firm when moist.

Table (1): Soil physical properties

Soil depth cm	Mechanical analysis				Bulk density (gm/cm)			Cole	Water retention %		Water available		H.C Cm/h	Porosity %
	C. Sand	F. Sand	Silt	Clay	Air dry	O.D.	1/3 bar		FC 1/3 bar	DWP 15 bar	Wt %	Value		
0-15	1	2	28	69	1.79	1.73	-	-	48.3	24.7	23.6	33.4	0.23	32.45
15-45	2	2	28	68	1.88	1.88	1.03	0.22	48.5	24.8	23.7	34.8	0.72	33.58
45-80	2	2	27	69	1.85	1.87	1.02	0.22	50.9	26	24.9	36.1	0.47	30.19
80-110	2	2	28	68	1.84	1.81	1.04	0.2	53.3	27.2	26.1	37.3	0.30	30.57
110-150	1	2	27	69	1.85	1.88	1.06	0.2	52.2	26.6	25.6	37.7	0.25	30.18

Crop data: Grain sorghum (*Sorghum bicolor*) in Gadaref state (rain fed agriculture) usually planted in July and harvested in November with following properties:

- Maximum yields of high-yielding varieties adapted to the climatic conditions of the available growing season, adequate water supply, and high level of agricultural inputs is 3.5-5ton/ha.

Sensitive Growth Periods for Water Deficit: Flowering and yield formation are more sensitive than vegetative period. However, the vegetative period itself is less sensitive when followed by ample water supply.

- Length of crop development stages, crop coefficients (Kc), mean maximum plant heights, maximum effective rooting depth, maximum depletion factors, maximum crop salt tolerance levels and yield response factor (Ky); as shown in Table (2) (Doorenbos and Kassam, 1979; Ayers and Westcott, 1985; Allen *et al*., 1998).

Table (2): Grain sorghum crop data

<table>
<tr><td colspan="3">Stages</td><td>Init (Lini)</td><td>Dev. (Ldev)</td><td>Mid (Lmid)</td><td>Late (Llate)</td><td>Total</td></tr>
<tr><td colspan="3">Length of stage (days)</td><td>20</td><td>35</td><td>45</td><td>30</td><td>130</td></tr>
<tr><td colspan="3">Kc</td><td>-</td><td>-</td><td>1-1.1</td><td>0.55</td><td>-</td></tr>
<tr><td colspan="3">Max. crop height (h)(m)</td><td colspan="5">1-2</td></tr>
<tr><td colspan="3">Max. rooting depth (m)</td><td colspan="5">1-2</td></tr>
<tr><td colspan="3">Depletion fraction(for ET _ 5 mm/day) p</td><td colspan="5">0.55</td></tr>
<tr><td colspan="3">Max ECedS/m</td><td colspan="5">18</td></tr>
<tr><td colspan="8">yield response factor (Ky)</td></tr>
<tr><td colspan="3">Vegetative period</td><td colspan="2" rowspan="2">Flowering Period</td><td rowspan="2">Yield formation</td><td rowspan="2">Ripening</td><td rowspan="2">Total Growing period</td></tr>
<tr><td>Early</td><td>Late</td><td>Total</td></tr>
<tr><td>-</td><td>-</td><td>0.2</td><td colspan="2">0.55</td><td>0.45</td><td>0.2</td><td>0.9</td></tr>
</table>

Data Analysis

BUDGET software (Rase, 2003) was used as a main tool to attain study objectives. Input data need to be prepared as prerequisite to use BUDGET software. Two-computer models ETo and RAINBO (Raes *et al*. 1996) were used to achieve this target. The data was analyzed using descriptive statistics.

Results and Discussion

The result obtained by BUDGET program gives the potential evaporation (Epot), potential transpiration (Tpot), potential evapotranspiration (ETpot), actual evaporation (Eactu), actual transpiration (Tactu), actual evapotranspiration (ETactu), water stress, runoff and number of days before water stress occurs.

From Table (3) we use water stress and runoff and calculate the ratio of water harvesting (WH) at probability of 67% and efficiency factor range 0.5 to 0.75 which recommended by FAO (1991). At 67% probability we find the ratio range between 3.16:1 to 2.12:1 at efficiency factor 0.5 to 0.75, respectively, this result is similar to the result recommended by FAO (1991) which report in most cases it is not necessary to calculate the ratio C:CA for system implementing fodder production and/or rangeland rehabilitation. As general guideline, a ratio of 2:1 to 3:1 for micro catchments (which are normally used) is appropriate. When we calculate the efficiency factor using the rain fall and evaporation data we obtained an efficiency factor of 0.74. This result is similar to value recommended by FAO (1991). By using this value we find the ratio C:CA is 2.18:1 at probability 67% and when we use the median value of water stress and run off of 30 years (1980 – 2009) we find the ratio of C:CA is 3.8:1. The reservoir capacity is 927 m^3/fed.

Table (3): Stress, runoff, reservoir capacity and C/CA ratio

Stress Mm	Stress/fed m^3	20%loss Evap+seepage	Reservoir capacity m^3	Runoff mm	Runoff/fed m^3	Efficiency %	C/CA
181.1	773.22	154.644	927.864	109.7	460.74	74	2.72143

The reservoir capacity does not include the amount of water consumption by Human and Animal.

Table (4): Results obtained by budget program

Years	Epot Mm	Tpot Mm	ETpot Mm	Eactu Mm	Tactu mm	ETactu mm	Water stress Mm	Runoff Mm	No. of days before tress
1996	184.8	458.2	643	184.8	84.4	269.2	373.8	209.1	30
1997	175.7	462.4	638.1	175.7	73.4	249.1	389	146.7	23
1998	175.7	462.4	638.1	175.7	82.4	258.1	380	219.2	28
1999	166.6	432.7	599.3	166.6	93.6	260.2	339.1	264.6	23
2000	183.4	482.5	665.9	183.4	88.4	271.8	364.1	125.2	25
2001	174.7	450.2	624.9	174.7	420.9	595.6	29.3	0	98
2002	182.9	443.6	626.5	182.9	78	260.9	365.6	270.4	23
2003	174.5	451.3	625.8	174.5	72.2	246.7	379.1	265.7	23
2004	180.2	462.8	643	180.2	389.8	570	73	0	91

Conclusion

By using the water stress, runoff 67% probability and 0.74-coefficient factor, we find the ratio C/CA is 2.7:1 and the reservoir capacity is 927m^3. BUDGET is public domain software which can be easily downloaded from web.

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