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ORIGINAL ARTICLES

Effects of some *in-situ* water harvesting techniques on soil moisture and sorghum (*Sorghum bicolor* (L.) Moench) production in Northern Gedaref State

[1]Adil Bashir Karrar, [2]Hassan Ibrahim Mohamed, [3]Haitham Ragab Elramlwai, [4]Amir Bakhit Saeed and [5]Atif Elsadig Idris

[1]Dep. of Agric. Engineering, Faculty of Engineering, University of Sinnar, Sudan.
[2]Dep. of Agric. Engineering, College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum North, Sudan.
[3]Centre of Dry Land Farming Research and Studies, University of Gadarif, Sudan.
[4]Dep. of Agric. Engineering, Faculty of Agriculture, University of Khartoum, Shambat, Khartoum North, Sudan.
[5]Dep. of Agronomy, College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum North, Sudan.

ABSTRACT

Rainfall fluctuations, dry spells and drought are the main constraints for rain fed agriculture development in Sudan. In recent years the yield and productivity of sorghum have been declining drastically. This is mainly attributed to the lack of appropriate soil and rainfall management practices. This situation is envisaged can be improved under the prevailing conditions of Sudan by adopting simple water harvesting techniques with the intention of raising and sustaining sorghum productivity of the small holdings (about 50 ha). Accordingly a study was conducted to investigate the effect of some *in-situ* water harvesting techniques on performance of sorghum crop with respect to soil moisture content, yield and yield components of sorghum crop. Treatments tested were contour ridge (CR), tied ridge (TR), ridge furrow (RF) and wide level disc (WLD). The results showed that water harvesting techniques resulted in better moisture retention and hence crop yield.

Key words: *in-situ* water harvesting techniques, soil moisture, sorghum grain yield.

Introduction

Considering the persistently growing pressure on finite freshwater and soil resources, it is becoming increasingly clear that the challenge of feeding tomorrow's population is to a large extend about improving productivity of water within present land use, as new arable land is relatively limited.

Ninety-five percent of current population growth occurs in developing countries with a significant proportion still depending on a predominantly rain fed-based economy. Unfortunately, in several regions, including Africa in general and the Sudan in particular, rain fed agriculture has generally been associated to low yield levels, and high on-farm water losses.

During recent decades the interest in water harvesting has increased as agriculture and water projects based on high energy input and sophisticated technology appear unsustainable. Several national and international bodies have launched programs to investigate the potential of water harvesting but it is well recognized that much has to be done in order to clearly identify their real capabilities in several environment conditions as the overall success is much less than expected in combining technical efficiency with low cost and acceptability to potential beneficiaries. Much of the efforts of the international bodies are concentrated in Africa, for sure due to the critical social, economical and environmental situation verified in several countries of this continent.

Adopting water harvesting techniques is expected to provide water quantity and quality for both irrigation and domestic use, reduce crop yield fluctuation, reduce risk of investment in rain-fed agriculture, improve pastures, reduce use of groundwater in agriculture, save soil fertility, and increase groundwater recharge. Moreover, the low input of water harvesting techniques makes it economically available for everyone, especially the poor traditional farmers. Water harvesting is easier to develop than any other water resources as well as water harvesting can be easily integrated with indigenous knowledge.

The population of the Sudan is 33.3 million people as estimated in mid-2010. Of this population, 11 million people will be concentrated in Khartoum and Gezira, which explains the degree of development activity concentrated in those areas. Agriculture contributed 40 percent of the GDP in 2005, of which 25 percent was from crop production while 20 percent was from livestock. Agriculture remains the main source of non-oil contributions to the GDP, just ahead of services and construction and much ahead of industry. The sector also

Corresponding Author: Atif Elsadig Idris, Dep. of Agronomy, College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum North, Sudan.
E-mail: atifelsadig@yahoo.com

provides employment and household income in rural areas, with about 80 percent of the labor force employed in agriculture and agro-industries. The agriculture sector is usually divided into two subsectors: irrigated and rain fed (traditional and semi-mechanized). The irrigated subsector, accounting for 1.8 million ha, provided 31 percent of domestic cereal production in 2008 while some 8.5 million ha of rain fed food crops produced the remaining 69 percent of mostly cereals grown in the northern states from an estimated arable area of 19 million ha in the whole country.

Rainfall fluctuations, dry spells and drought are the main constraints for rain fed agriculture development in Sudan. Based on the Sudan water demand projection up to the year 2027, the total annual demand of Sudan would be 46.2 BCM, while the current total available water is 30 BCM. Currently Sudan population growth (2.9%), and accordingly the Sudan population would be 56 million by the year 2030. The irrigated area is expected increase to 2.44 million hectare, which is only 4% of total arable land (84 million ha). The conclusion is that there is a wide gap ought to be bridged while the limiting factor for agricultural expansion in Sudan is water and not the land. However, the average annual amount of rainfall in Sudan is more than 10 times the average annual discharge of the Nile River. Enhancing water use efficiency as well as water management techniques, especially rain water, would mitigate such shortages, and would maximize the socio-economic and environmental benefits for Sudan. Consequently, without doubt, water harvesting is a key element for Sudan future development projects and peace. In fact, many observers believe that the conflict in Darfur has started as a competition over water resources, before inflamed by all kinds of political drivers. In general, rain fed agriculture is practiced in most of the rural areas of the Sudan; hence water harvesting is expected to play a significant role in terms of socio-economic development. Promoting sustainable water management through research in water harvesting is a necessity.

The rationale of Water Harvesting:

Water harvesting in its broadest sense is an umbrella term covering a wide range of techniques and methodologies to collect and conserve various forms of runoff water, originating from ephemeral water flows generated during tropical rainstorms. In this sense we adopt a similar approach as the definition by Siegert (1994) of water harvesting as “the collection of water for its productive use”. Water harvesting focuses on improving the productive use of rainwater on the local scale (field to sub-catchment scale) before the runoff water leaves the geographical unit in question. The aim is to mitigate the effects of temporal water shortages to cover both domestic and agricultural needs. In terms of upgrading rain fed agriculture, water harvesting can be categorized according to three broad objectives:

1) Systems that improve infiltration of rainwater into the soil.
2) Systems that prolong the duration of soil moisture availability in the soil.
3) Systems that store surface and sub-surface runoff for later use.

Water harvesting incorporates a broad set of techniques and methodologies that can be grouped in three main domains (namely *in-situ* moisture techniques, runoff farming and spate irrigation).

The central clay plains of the Sudan where most rainfed crops are grown are flat in nature (15 cm/km). Hence, in such soil it is more effective to look into rainwater management techniques that tend to store more water within the soil and eliminate most of runoff water.

The main objective of this article is to compare the effect of different water harvesting techniques such contour ridges, tied ridges, and ridge furrow with harrowed soil surface (conventional plowing method) on soil moisture status within the root zone (60 cm depth) throughout the season (during early, mid and late season), and the yield and yield components of sorghum crop under rain-fed conditions.

While the specific objectives are:

1. to study the effect of three water harvesting techniques i.e. contour ridge (CR), tied ridge (TR), ridge furrow (RF) and the conventional method of corrugated soil surface using wide level disc (WLD), on the yield and yield components of sorghum.
2. to study the effect of aforementioned techniques on the status of water on the surface and in the soil within the root zone throughout the season (during early, mid and late season).

Review of Rainwater harvesting Techniques:

The Concept:

Arid and Semi-arid zones are characterized by low erratic rainfall of up to 700 mm per annum, periodic droughts and different associations of vegetative cover and soils. In the Semi-arid zones inter-annual rainfall varies from 20-50 % with averages of up to 700 mm (CASL, 2006).

The majority of the population in the Arid and Semi-arid areas depend on agriculture and pastoralism for subsistence. There is a need of a more efficient capture and use of the scarce water resources in Arid and Semi-arid areas. An optimization of the rainfall management, through water harvesting in sustainable and integrated production systems can contribute for improving the small-scale farmers' livelihood by upgrading the rain fed agriculture production.

In crop production systems, rainwater harvesting is composed of a runoff producing area normally called catchment area and a runoff utilization area usually called cropped basin. The major categories are classified according to the distance between catchment area and cropped basin as follow: In-situ rainwater harvesting, Internal (Micro) catchment rainwater harvesting and External (Macro) catchment rainwater harvesting and spate irrigation (flood water harvesting) (Hatibu, and Mahoo, 1999).

Other important requirements to be considered in the implementation of water harvesting systems for crop production are the slope of the area and operation costs. Such techniques are not recommended for areas where slopes are greater than 5 %, due to uneven distribution of runoff and large quantities of earthwork required which is not economical (Critchley & Siegert, 1991). Labor cost for construction and maintenance of water harvesting systems is the most important factor to be considered, which determines if a technique will be widely adopted at the individual farm level. Many farmers in arid and semi-arid areas do not have the manpower available to move large amounts of earth that is necessary in some of the large water harvesting systems (Rosegrant *et al*., 2002).

Types of water harvesting techniques:

According to (Nasr, 1999), there are two basic types of runoff-farming systems:

Direct water application system, where the runoff water is stored in the soil of the crop growing area during the precipitation and supplemental water system, where the collected water is stored offsite in some reservoirs and later used to irrigate a certain crop area.

Some of the typical examples reported by (Prinz, 2002) and (Critchley and Siegert, 1991) are:

a) Inter-row water harvesting: Inter-row water harvesting is applied either on flat land or on gentle slopes of up to 5% having soil at least 1 m deep. The annual rainfall should not be less than 200 mm/year. On flat terrain (0-1% inclination) bunds are constructed, compacted and under higher-input conditions, treated with chemicals to increase runoff. The ridges of about 0.40 m height are built 2 to 20 m apart, depending on slope, soil surface treatment, general CCR and type of crop to be grown. On sloping land, this system is recommended only for areas with a known regular rainfall pattern; very high rainfall intensities may cause breakages of the bunds. Crops cultivated in row water harvesting systems are maize, beans, millet, rice or (in the USA) grapes and olives (Pacey and Cullis, 1986; Finkel and Finkel, 1986; Tabby, 1994). The preparation of the land for inter-row water harvesting can be fully mechanized.

b) Micro-catchments systems: Micro-catchments water harvesting (MC-WH) is a method of collecting surface runoff from a small catchments area and storing it in the root zone of an adjacent infiltration basin. This infiltration basin may be planted with a single tree, bush or with annual crops (Boers and Ben-Asher, 1982). Their main characteristics include simple to design and cheap to install, therefore easily replicable and adaptable, higher runoff efficiency than medium or large scale water harvesting systems and have no conveyance losses.

c) Medium-sized catchments water harvesting: Water harvesting from medium-sized catchments (1,000 m^2 – 200 ha) is referred to by some authors as "water harvesting from long slopes", as "macro-catchments water harvesting" or as "harvesting from external catchments systems" (Pacey and Cullis, 1988; Reij et al., 1988). It is characterized by the C/CA ratio is 10:1 to 100:1; the catchments being located outside the arable areas. The catchments area may have an inclination of 5 to 50%; the cropping area is either terraced or located in flat terrain.

d) Large catchments water harvesting: Large catchments water harvesting comprises systems with catchments being many square kilometers in size, from which runoff water flows through a major Wadi (bed of an ephemeral stream), necessitating more complex structures or dams and distribution network.

In-situ rainwater harvesting:

In-situ rain water harvesting, also called soil and water conservation, involves the use of methods that increase the amount of water stored in the soil profile by trapping or holding the rain where it falls (Hatibu & Mahoo, 1999; Stott *et al*., 2001). In this application there is no separation between the collection area and the storage area, the water is collected and stored where it is going to be utilized (UNEP, 1997). It is basically a prevention of net runoff from a given cropped area by holding rain water and prolonging the time for infiltration. This system works better where the soil water holding capacity is large enough and the rainfall is equal or more than the crop water requirement, but moisture amount in the soil is restricted by the amount of infiltration and or deep percolation (Hatibu & Mahoo, 1999).

The *in-situ* rainwater harvesting for crop production purposes is better achieved by the means of conservation tillage, conservation farming and conventional tillage. Such physical conservation measures involve land shaping, the construction of contour bunds, terraces and ridges (FAO, 1993).

Ridge tillage has been defined as "a method of land preparation whereby the topsoil is scraped and concentrated in a defined region to deliberately raise the seedbed above the natural terrain" (Lal and Vandoren, 1990). Crops are 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 take the advantage of the wetter condition of the soil under the furrow. It is an effective water management and 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 Onstah 1977 and Storey, 2003). 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 (known either as tied-ridging, furrow blocking or basin tillage) (Gardner *et al*. 1999). In clayey 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. In Zimbabwe; Piha (1993) and Vogel (1993), in Botswana; Carter and Miller (1991) and in Burkina Faso; Hulugalle and Malton (1990) have shown similar results of more retained water and less runoff. Similar results were also obtained in USA; Krishna (1989).

Growing a crop on or between ridges has the following advantages and disadvantages:

On lightly sloping land, ridges along the contour can curb rainwater runoff and thus erosion by increasing the surface relief; however, tillage along the contour lines is complicated, especially if a particular field has slopes in more than one direction, it can easily lead to increased erosion; in high rainfall areas and poorly drained soils, ridges allow a better water management; on the other hand, ridges often dry faster and will take longer to wet after a dry spell, and germination of a crop planted on ridges is quite often observed to be slower than a crop planted on flat land; by ridging, any organic matter or fertilizer which is present at or near the soil surface, will be concentrated in the ridge and will thus be of greater benefit to the crops (Meijer, 1992).

Contour ridges, sometimes called contour furrows, are small earthen banks, with a furrow on the higher side which collects runoff from an uncultivated strip between the ridges. In Israel and North America they are called 'desert strips'. Through their shape, soil moisture is increased under the ridge and the furrow, in the vicinity of plant roots. The advantage of this system is that the runoff yield from the short catchment length is very efficient. Labor requirements are relatively low and contour ridges are easy to make using hand tools. Ridging is done by constructing small earth banks parallel to the contours of a slope.

A variation on ridging is the partitioned furrow technique, better known as tied-ridging. In this system lower ridges, cross-ties (15-20 cm high), are made every few meters across the contour furrows, creating mini-basins. In case of light rainfall, the water remains in the mini-basins. When rainfall is heavy, the water runs off over the cross-ties along the contour, because the cross-ties are lower than the ridges and the furrows are built at an angle to the contour. Tied-ridging can be used only where rainfall does not exceed the storage capacity of the furrows; otherwise severe erosion may be the result. The construction and maintenance of ridges is hard work, especially on heavy (clayey) soil. In order to spread the work out, in the first year the contour ridges can be ploughed using an ox-plow or tractor drawn implement with a reversible blade and the cross-ties can be made by hand.

Experience of Water Harvesting in Sudan:

In the Sudan, many indigenous water-harvesting techniques are practiced in different parts of the country e.g. Jebel Marra area and Red Sea Hills. The local people in Western Sudan, in general, use several techniques; namely, Haffirs, Rahads, Fulas, and Turdas, beside many other techniques to harvest water for agriculture and domestic use. In Southern Darfur, the local people grow pearl millets, groundnut and sesame on sands and grow cowpea, sorghum, fruits garden and vegetables on clay, and valley soils using indigenous water harvesting techniques (Reij, *et al*., 1986).

The harvesting of sheet flow runoff is traditional techniques practiced in many parts of the Sudan (Van Dijk, 1991). It was found to be very successful for establishing trees under semi-arid conditions.

The Terras is a relatively elevated land non-flooded by Khors to utilize runoff water on steep slopes. This is accomplished by constructing U-shape bunds across the slope of rolling lend to arrest or trap sheet flow runoff generated after rain storms on catchments usually 2-3 times the size of the cultivated land (Van Dijk, 1991; Critchley and Reij, 1989). Simple stone lines and earth bonding systems are found in Eastern Sudan.

Water harvesting reduces the increasing pressure over the (limited) blue water. In the Nile Basin, only 5% of the rainfall comprises the river discharge (blue water). However, water harvesting, utilizes part of the rain which hardly finds its way to the Nile. This increases water productivity in general, while relaxing the mounting tension over the limited Nile water.

Production of Rainfed Sorghum:

Sorghum (Sorghum bicolor L. Moench) is the world's fifth major cereal crop after wheat, maize, rice and barely, in feeding human race (Onwueme and Sunha, 1999). It is the main staple food crop in Sudan. It is produced under a wide range of soil and climatic conditions, covering at least one-third of the total cropped area, producing about 75% of food grains in the country. Most of the sorghum areas lie in the central rain lands of the Sudan, in a belt between the 450 mm and 600 mm isohyets (Ali and Salih, 1972) provides, on average, about 66% of total sorghum production. It is grown as a dual-purpose crop, the grain being used for human consumption and the straw for animal feed. The sorghum straw can also be used as a building material, firewood and various other purposes.

In recent years the yield and productivity of sorghum have been declining drastically. This is mainly attributed to the lack of appropriate soil and rainfall management practices. This situation is envisaged can be improved under the prevailing conditions of Sudan by adopting simple water harvesting techniques with the intention of raising and sustaining sorghum productivity of the small holdings (about 50 ha).

The agriculture policy of the country has been directed towards expanding areas of irrigated sorghum. Many reasons have enforced the adoption of this policy; the most important is perhaps the drastic decline in yield and productivity of sorghum under rain fed conditions. This is mainly attributed to many reasons the most important of which is erratic occurrence of rainfall with spatial and temporal variability and uncertainty (Mohammed et al. 2003, Ahmed and Naggar 2003 and Omer et al. 2003).

Such factors and many others have raised growing interest for remedies and improvements of the existing situation.

Water harvesting techniques are postulated in this study to improve the management of the water status, either in the form of surface water (run off) or as soil moisture. It is unfortunate that water harvesting techniques are often overlooked as attractive options to increase sorghum yield and to help Sudanese people to alleviate poverty, attain some degree of food security and reduce massive immigration towards large cities.

Materials and Methods

This study is directed to investigate *in-situ* water harvesting techniques for Sorghum production in Gedaref State. The State lies in the far eastern part of Sudan over 71,000 km^2 between latitudes 12.67° and 15.75° N and longitudes 33.57° and 37.0° E. About 3 million hectares (ha) are put under MA. The State stretches from north to south over three climatic zones with higher summer temperatures and warm winter (van der Kevie 1973). Rainfall is during the period of May to October. The climatic zones, as described by van der Kevie and Buraymah (1976) are:

* The arid zone, with rainfall varying from 200-400 mm.
* The semi-arid zone, with rainfall varying from 400-600 mm.
* The dry monsoon zone, with rainfall varying from 600-800 mm.

This rainfall status and the vast areas of dark cracking soils (Vertisols) make Gedaref State to be the main state in rain fed crop production in Sudan.

The experiments were conducted at the Demonstration Farm of the Faculty of Agricultural and Environmental Sciences, University of Gedaref at Twawa area (Long. 35.24° E, Lat. 14.02° N and Altitude. 602 m AMSL) for two consecutive seasons in 2006/07 (FS) and 2007/08 (SS). Soil of the experimental site is predominantly Vertisols, deep, dark-colored clays of montmorillonitic origin (clay content is 40-65 %). It is characterized by low infiltration rate (2-3 mm/hr), low nitrogen content (0.012 %), low in organic matter (1.4 %) and high pH (8.4). Most recent observations (1975-2004) show that the area is receiving mean annual precipitation of 603 mm.

Three *in-situ* water harvesting techniques, namely, Contour ridges (CR), tied ridges (TR), and ridge furrow (RF) were compared to harrowed soil using wide level disc (WLD), during the two consecutive seasons to study their effect on soil moisture status and yield and yield components of sorghum in the northern area of Gedaref State.

Treatments tested were contour ridge (CR), tied ridge (TR), ridge furrow (RF) and wide level disc (WLD). Randomized Complete Block Design with four replicates was adopted for the layout of the experiment and for data analysis. The plot area was 15*20 m. Buffer zones were left between plots and around the experiment area to facilitate crop management operations. A (10*10 m) grid map was prepared for the experiment area by using surveying equipments. It reveals that a mild slope of about 0.07% dominates the area. One contour base line for each CR treatment was selected such as to divide the area into approximately two equal parts. The ridges 15-20 cm height were laid out to follow the contour base line. Ridges, in CR, TR and RF treatments, of 0.8 m spacing were constructed using a ridger implement mounted on a 75 hp Massy Ferguson tractor.

Cross earth ties in TR, 8-12 cm in height, were manually constructed with hoes at 1.5 m apart. Sowing in TR was done on top of the ridge and in RF was done in the furrow. WLD treatment was done using a wide level disc harrow (WLD) connected to Massy Ferguson tractor of 75 HP, with a seed rate of 7.0 kg/fed as recommended by Agricultural Research Corporation.

Moisture stored in each of the four treatments was determined in the form of depth (mm) of water stored in the top 0.6 meter soil depth (assumed to be the depth of the root zone in this type of heavy soil). The soil water stored (%) in each 0.2 m incremental depth down to 0.6 m was determined gravimetrically. It was then converted to water depth (mm) by multiplying by the specific bulk density values measured by the core sampler methods as described by Blake (1965). Three measurements of soil moisture content were conducted at three periods (viz. early, mid and late season) during both growing seasons. Arfa′a Gadamak, (*Sorghum bicolor* L. Moench), a rainfed sorghum cultivar, was used as an indicator crop to study its performance under the studied *in-situ* rainwater harvesting techniques. About a month after sowing, plots were manually weeded and thinned to 2 plants per hole.

Infiltration rate measurements were done using double ring infiltrometer method, taken once at the end of the growing season. The procedure followed was that outlined by Michael (1978) for WLD treatment. One location per treatment for each replication was selected randomly, but noticeable cracks were avoided. For the ridge and furrow treatments the blocked furrow infiltrometer procedure outlined by Trout and Hart (1982) was followed. A furrow section was selected to reflect real field situations. Two metal sheets of 1*1 m^2 were driven into the soil to a depth of approximately 15 cm and 1.0 m space to form a small furrow segment. Similarly four metal sheets were installed in the parallel buffer furrows. The bottom of the test furrow was covered with plastic sheet. Then the test furrow segment was filled with water to a depth of about 15 cm. The buffer furrows were also filled with water to the same depth. The plastic sheet was gently removed and time was recorded. Level of pounded water measured using graduated scale against predetermined time intervals of 5, 10, 20, 25, 30, 60, 90, 120, 180 and 240 minutes. The level of water in the test furrow and buffer furrows was restored back by refilling with water from a measuring container throughout the test. Then the Kostiakov formula was used to calculate cummulative infiltration (Z and T). Then the data was correlated using least-square method. The resultant formula was used to calculate instantaneous infiltration rate (I mm min^{-1}) at any time T by differentiation as follows:

$$I(T) = dZ/dT = nkT^{n-1}$$

Substituting the values of n and k in the resultant equation, infiltration rate equations for the different treatments were determined during both growing seasons.

For stem diameter five samples from each plot were randomly selected and the stem diameter was measured two times in the season viz. early and late season, using a vernier at the middle of the stem. To measure plant height, five samples from each plot were randomly selected for plant height measurement two times in the season viz. early and late season, using a 2 m long measuring rod. For days to 50% flowering, direct counting of flowering heads using the one-half square meter quadrant. Three samples were taken randomly from each plot. The percentage of flowering plants was estimated by using the following relation:

% flowering plants= [Number of flowering plants/Total number of plants] *100

Then the number of days required for 50% flowering was recorded. For plant density, numbers of plants per meter square was calculated using a one-half square meter quadrant thrown randomly over the growing plants three times per plot. For dry matter a 0.5 m^2 quadrant was thrown randomly over the growing plants in each plot at the end of the growing season; the plants were cut, tied in bundles and left to dry for 10 days under the sun and then weighed to give the air-dry yield. To get grain yield, a one-half square meter quadrant was thrown randomly over the growing plants in each plot at the end of the growing season; the heads were cut and the grains were threshed and weighed and yield per square meter was recorded.

Analysis of variance appropriate for complete randomized block design was applied by adopting IRRISTAT software (IRRISTAT, 2005).

Result and Discussion

Amounts of seasonal rainfall (mm) measured during the two rainy seasons were 511.4 mm and 542.4 mm for the first (FS) and second season (SS) respectively. They were less than the long-term average of Gedaref town (603 mm). Rainfall was measured at the site. It was less than the long-term average of Gedaref town (600 mm) in the first and second seasons according to Gedaref Metrological Station, 2005. Using the conventional tillage machine (WLD) may not help to conserve enough water for sorghum production, mainly due to the low infiltration rate of the Vertisols and its tendency to form compact surface crust that induces runoff. High intensity rain showers also enhance water losses through runoff. Crop growth conditions may further be hampered by a number of climatic factors, such as low and erratic rainfall, low humidity levels and high temperature during growing season (Botha et al. 2003).

Variation of soil moisture content (SMC):

Soil moisture content (SMC) of the soil profile (60 cm) was measured at three periods, i.e. at early season (P1), mid season (P2) and late season (P3). The effects of the treatments on SMC at P1, P2 and P3 during the first (2006/2007) and second (2007/2008) seasons are shown in table (1). In both growing seasons at all measurement periods, the results obtained showed significant (P>0.05) difference in SMC between *in-situ* water harvesting treatments and WLD. Where, *in-situ* water harvesting treatments (TR, RF and CR) recorded SMC values higher than WLD in both seasons. The apparent higher SMC in the SS than FS was only due to rainfall variability through the growing season. This result is in agreement with Ibrahim (2008), Mohammed (2009), Li *et al*. (2000), Tian *et al*. (2003), and McHugh *et al*. (2007).

Table 1: Treatments means for SMC (mm) of the root zone during the two seasons and the three growing periods.

Treatment	First Season			Second Season		
	P1	P2	P3	P1	P2	P3
WLD	201.946^{a}	189.901^{a}	171.427^{a}	281.177^{a}	179.207^{a}	163.610^{a}
RF	221.597^{b}	215.022^{b}	192.093^{b}	292.739^{ab}	210.283^{b}	208.104^{b}
TR	219.063^{a}	203.997^{b}	186.770^{b}	292.892^{ab}	212.749^{b}	216.553^{b}
CR	227.782^{b}	213.228^{b}	191.078^{b}	297.885^{b}	214.720^{b}	215.986^{b}
$LSD_{0.05}$	18.318	12.072	10.654	16.105	21.821	40.310

$LSD_{0.05}$ = least significant difference at 5% level.

Effect on infiltration rate:

Table (2) shows the means of the treatments of the initial infiltration rate (during 5 minutes from the beginning). There is significant difference (P>0.05) between all treatments in the FS. The difference is between TR, WLD and RF, however, CR do not differ significantly from TR and RF. values can be arranged in descending order as (TR), (CR), (RF), and (WLD) in the FS. This can be attributed to the good effect of ridging on the soil physical status. In the second season there is no significant difference. It is in the order of (TR)>(RF)=(WLD)>(CR) in the second season. The result also showed the superiority of the tested techniques over the conventional method in conserving their good effect on infiltration rate. This result is in agreement with Mohammed (2009).

Table 2: Average initial infiltration rate (after 5 minutes) for water harvesting treatments.

Treatments	Initial Infiltration rate FS	Initial Infiltration rate SS
WLD	0.185^{b}	0.245^{a}
RF	0.210^{c}	0.245^{a}
TR	0.325^{a}	0.290^{a}
CR	0.270^{ac}	0.185^{a}
$LSD_{0.05}$	0.081	0.152

$LSD_{0.05}$ = least significant difference at 5% level.

Less time to reach final intake rate give an indication of the easiness of water percolation into the soil and hence moisture content. Treatments were in the order (CR)<(RF)<(TR)<(WLD). This shows the superiority of the ridge-furrow system over the conventional system (Fig. 1).

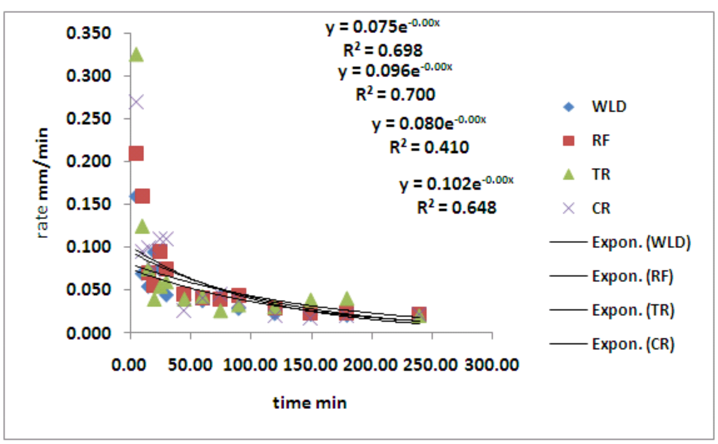

Fig. 1: Infiltration rate of the different techniques.

Precipitation use efficiency (PUE):

This parameter results are shown in table (3). It reveals that there is significant difference (p>0.05) between water harvesting techniques and WLD in the two seasons. In the FS was between RF and WLD are not significantly different. This result may be attributed to the difference in rainfall amount between the two seasons. Although there are no significant differences between the tested techniques they can be put in a descending order as TR, CR and RF and TR, RF and CR in the two seasons, respectively. This result is in contrast with Mohammed (2009) who found no significant differences in PUE in the FS, but significant difference was found in the SS, and in agreement with Li *et al*. (2001) and Li and Gong (2002) and Li *et al*. (2000).

Table 3: Average precipitation use efficiency (PUE) for conservation tillage treatments.

Treatments	PUE (FS)	PUE (SS)
WLD	0.403[a]	0.393[a]
RF	0.418[a]	0.441[b]
TR	0.447[b]	0.487[b]
CR	0.445[b]	0.440[b]
$LSD_{0.05}$	0.026	0.057

$LSD_{0.05}$ = least significant difference at 5% level.

Yield and Yield Components of Sorghum Crop (sorghum bicolor L.):

No significant differences between in-situ rainwater harvesting techniques and WLD in many of the yield components of sorghum crop in the two seasons. Parameters included stem diameter (SD cm), plant height (PH cm), days to 50% flowering (50%F days), plant density (PD No. of plants/m^2), grain yield (GY kg/ha), and dry matter (DM kg/ha). Tables (4) and (5) depict the means of these parameters. However, there is a significant difference in yield between the tested technique and WLD in the FS and SS. According to Carter and Miller (1991) and Gupta (1995 and 1999) water harvesting can improve soil moisture storage, prolong the period of moisture availability, and enhance the growth of crops. The result is in agreement with Ibrahim (2008), Mohammed (2009), McHugh *et al*. (2007), Belachew and Abera (2010).

Table 4: Means of yield and yield components in the first season.

Treatment	stem diameter (SD) early	stem diameter (SD) late	plant height (PH) early	plant height (PH) late	days to 50% flowering (50%F)	plant density (PD)	grain yield (GY)	dry matter (DM)
WLD	0.34[a]	1.76[a]	3.38[a]	88.35[a]	52.50[a]	25.00[a]	206.2[a]	1057.5[a]
RF	0.36[a]	1.95[a]	3.69[a]	93.20[a]	51.50[a]	28.00[a]	214.0[a]	1227.5[a]
TR	0.38[a]	1.87[a]	3.48[a]	93.10[a]	50.50[a]	33.00[a]	228.7[b]	1190.0[a]
CR	0.32[a]	1.75[a]	3.11[a]	93.20[a]	52.75[a]	30.00[a]	227.7[b]	1152.5[a]
$LSD_{0.05}$	0.06	0.23	0.81	18.77	2.30	7.69	13.35	461.05

$LSD_{0.05}$ = least significant difference at 5% level.

Table 5: Means of yield and yield components during the second season.

Treatment	stem diameter (SD) early	stem diameter (SD) late	plant height (PH) early	plant height (PH) late	days to 50% flowering (50%F)	plant density (PD)	grain yield (GY)	dry matter (DM)
WLD	0.39[a]	1.82[a]	4.08[a]	88.45[a]	54.00[a]	28.00[a]	213.2[a]	1070.00[a]
RF	0.37[a]	1.69[a]	5.22[b]	83.73[a]	53.25[a]	37.00[a]	239.0[a]	1300.00[a]
TR	0.33[a]	1.83[a]	3.44[a]	86.85[a]	54.50[a]	35.00[a]	264.0[b]	1282.50[a]
CR	0.29[b]	1.58[a]	3.97[a]	75.53[a]	54.75[a]	38.00[a]	238.5[a]	1200.00[a]
$LSD_{0.05}$	0.10	0.26	0.89	20.03	4.72	3.84	30.89	541.88

$LSD_{0.05}$ = least significant difference at 5% level.

Stem Diameter (SD) and Plant Height (PH):

As can be seen form tables (2) and (3), there are no significant differences in SD at the two periods of measurements, i.e. early and late season, in FS and SS. However, the values of the tested techniques can be put in a descending order as TR, RF and CR and RF, TR, and CR in the two seasons at early period, respectively. They can be put in a descending order as RF, TR, and CR and TR, RF and CR in the two seasons at late period, respectively. They were better than WLD except CR.

As can be seen form tables (2) and (3) that there no significant differences in PH in the two seasons at the two measurement periods i.e. early and late in the season. However, the values of the tested techniques can be put in a descending order as RF, TR and CR in the two seasons at early period. They can be put in a descending order as RF, CR, and TR and TR, RF and CR in the two seasons at late period, respectively (Fig. 2 and Fig. 3).

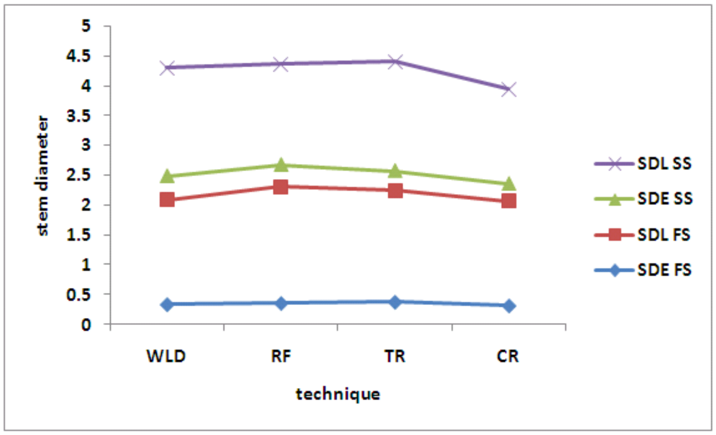

Fig. 2: Effect of treatments on the plant height in the two seasons (first (FS) and second (SS)) and at the two periods.

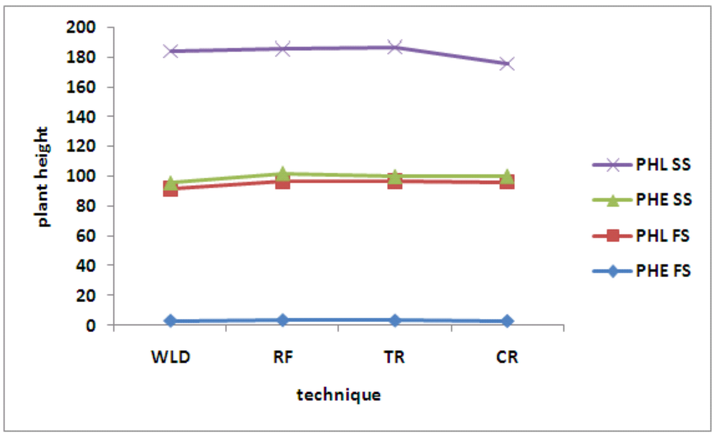

Fig. 3: Effect of treatments on the plant height in the two seasons (first (FS) and second (SS) and at the two periods.

Days to 50% Flowering (50% F):

As can be seen form tables (2) and (3) there is no significant difference concerning 50% flowering in the two seasons. In the FS and SS, CR technique recorded the highest number of days to 50% flowering. However, the values of the tested techniques can be put in a descending order as CR, RF and TR and CR, TR, and RF in the two seasons, respectively. This may be due to the higher moisture content that prolong the vegetative period (Fig. 4).

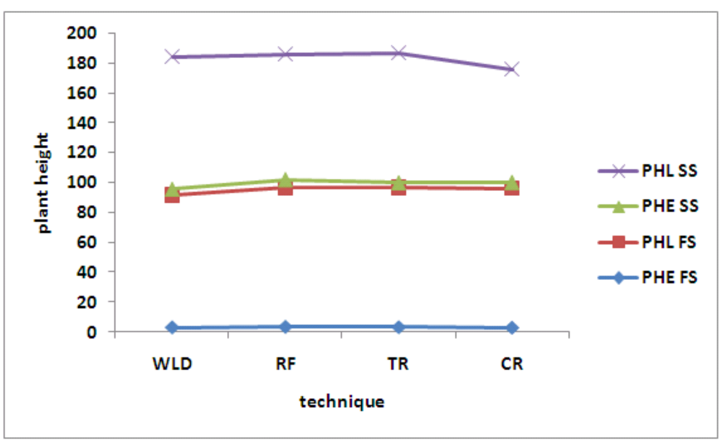

Fig. 4: Effect of treatments on fifty percent flowering in the two seasons (first (FS) and second (SS)).

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Plant Density (PD):

As can be seen form table (2) and table (3) that there was no significant difference between treatments during the two seasons. In FS and SS, the lowest value of PD was recorded under WLD, 25 plants/m^2 and 28 plant/m^2, respectively. This may be attributed to the low amount of moisture that stored in the root zone and the formation of hard crusts at soil surface as well as the inaccurate seeding depth under that treatment. However, the values of the tested techniques can be put in a descending order as TR, RF and CR and CR, RF, and TR in the two seasons at early period, respectively. They can be put in a descending order as RF, TR, and CR and TR, RF and CR in the two seasons, respectively. This is in agreement with the findings of Hemmat (1996), Karlen and Gooden (1987) and Halfmann (2005), who reported that soil compaction has an adverse effect on plant properties such as seedling emergence, root growth and crop yield. He recommended sub-soiling and deep plowing to alleviate soil compaction. Soil water status influences seed germination and seedling emergence through its effect on the rate of water imbibitions, which is governed by hydraulic conductivity of soil (Collins-George and Sands, 1959), the degree of seed-soil contact (Hadas and Russo, 1974) and differences in osmotic and matrix potential between bulk soil and the soil in close proximity to the seed (Collis-George and Sands, 1959 and Rose and Hegarty, 1979). The highest PD value in FS was recorded under TR and CR, 33.00 and 30 plant/m^2, whereas in SS RF and CR recorded the highest values, 37 and 38 plant/m^2, respectively. These results can be attributed to the advantages provided by *in-situ* water harvesting techniques, i.e. breaking soil crust, improving soil tilth (Unger, 1984), enhancing soil infiltration, and partial filling of the cracks which may improve the germination and emergence conditions and thus increase PD. Additional advantage due to planting in RF is that rainwater falling on the ridges can be re-collected in the planting belts (furrows) and thus can increase the availability of soil moisture to plant roots. It presents the advantage of the water harvesting techniques. This result is in agreement with Ren (2008) (Fig. 5).

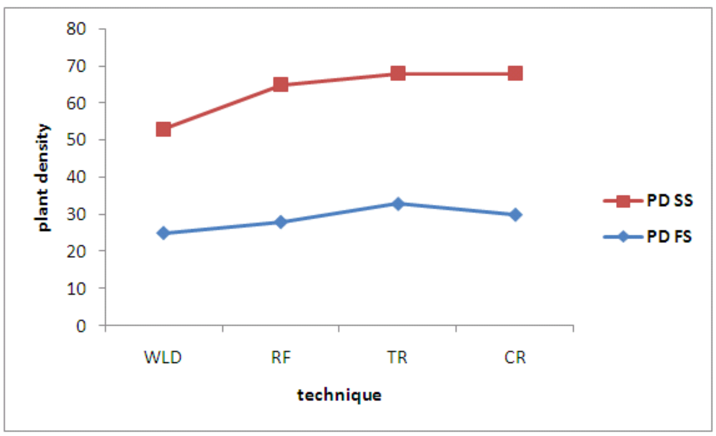

Fig. 5: Effect of treatments on plant density in the two seasons (first (FS) and second (SS)).

Dry Matter (DM) and Grain Yield (GY) in the FS and SS:

As shown in tables (2) and (3) treatments have no significant difference in the dry matter (DM) during the two seasons. The lowest DM values in the FS and SS were 1057.50 and 1070.00 g/m^2 recorded by WLD, respectively.

Tables (2) and (3) indicated that the treatments have significant ($P>0.05$) differences in GY during FS and SS. The lowest GY values in the FS and SS were 206.25 and 213.25 g/m^2 recorded under WLD, respectively. However, the RF and the RF and CR techniques do not significantly differ from WLD in the two seasons, respectively.

The low dry matter (DM) and grain yield (GY) obtained under WLD treatment was mainly due to the increased weed infestation, low plant density, poor soil-seed contact and soil compaction associated with the use of the WLD for seeding. The low dry matter (DM) and grain yield (GY) obtained under WLD is in line with the findings of Hemmat (1996) and Karlen and Gooden (1987) (Fig. 6).

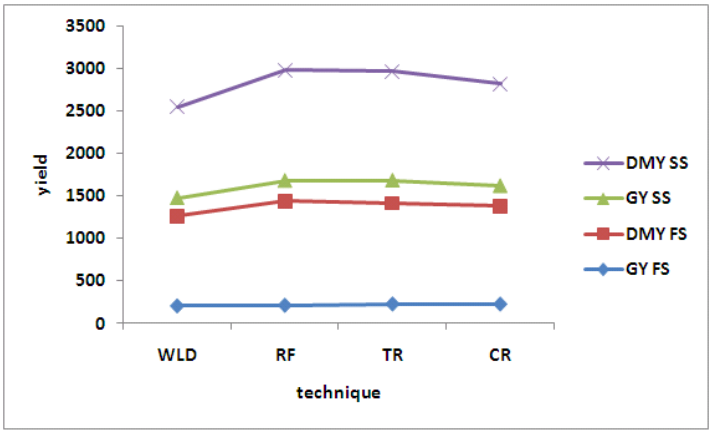

Fig. 6: Effect of treatments on grain and dry mater yield in the two seasons (first (FS) and second (SS)).

An important challenge for modern agronomy is to predict crop yield before harvesting and to estimate soil-crop characteristics during growing season by means of crop growth models. However, an important limitation, which prevents to reach that aim, is that the crop growth models are driven by a large amount of input parameters (crop, soil and weather data), which are not always available during the growing season and in the space. Whisler *et al*., (1986) stated that empirical models describe relationships between variables without referring to any underlying biological or physical structure that may exist between the variables. A big drawback to statistical models is that very often they will be location-specific and, while given good results in average or near average conditions, they may not reflect the real conditions in extreme weather situations. To predict grain yield depending on soil moisture content and the water harvesting technique empirically actual yield was curve-fitted against moisture content at each period (P1, P2 and P3), and the constants were taken for each treatment. These constants were used to estimate yield by deriving a relationship for each treatment as follows:

Table 6: Coefficients of yield for each treatment as a function of soil moisture in various plant growth periods.

Treatment yield	_Co	_Early MCP1	_Mid MCP2	_Last MCP3	R^2
WLD	1301.997	-3.77581	0.286552	-1.6314	
FR	-493.813	3.47977	0.81898	-1.70281	
CR	604.0504	0.746313	- 0.000171	-2.7633	
TR	10000000	- 43972	3966.95	10284.23	

Where: _Co is the technique constant, _Early is the coefficient of early season moisture content, _Mid is the coefficient of mid season moisture content, _Late is the coefficient of late season moisture content, MCP1 is the early season soil moisture content (mm), MCP2 is the mid season soil moisture content (mm) and MCP3 is the late season soil moisture content (mm).

Conclusions:

The study revealed the potential advantages of *in-situ* water harvesting for semi-arid zones and in particular for Northern Gedaref, Sudan. Depending on the results of this work the following conclusions can be summarized as follows:

1- *In-situ* water harvesting techniques improved soil moisture stored within the root zone as compared to the conventional harrowing using the wide level disc, resulting in higher dry matter and grain yield of sorghum.

2- Ridge and furrow techniques were the best, but the distance between furrows, furrow height and ridges width in TR and CR as well as the distance between ties in TR, should be intensively studied to determine the best ratio of run-on to run-off area, also the possibility of growing more than one row per ridge.

3- *In-situ* water harvesting techniques conserve a good infiltration rate till the end of the season this appears in initial infiltration rate measured at the end of the seasons. Also they took less time to reach final infiltration which reflects the easiness of water percolation into the soil.

4- *In-situ* water harvesting techniques affect yield and yield component in an increasing manner especially grain and dry matter yield.

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