CHAPTER ONE

1. Introduction

1.1 Background and Justifications:

The global population is projected to continue on a rising trend (FAO. 1996; Mpande and Tawanda, 1998), more so in sub-Saharan Africa in general and in Sudan in particular, where food deficit is already a significant challenge (Pinstrup-Andersen et al., 1999). Competing demands for freshwater from industry and municipalities, as well as environmental problems such as climate change, will limit future extension of surface Nile freshwater for irrigation to cultivate land areas. With limited room for expansion of both agricultural land and the irrigated portion of the arable land from Nile Water (Rockström and Baron, 2007), additional food production will have to come from intensification of production in rain fed farming systems. Rockström et al. (2003) showed that it is possible to at least double rain fed staple food production by producing more crop per drop' of rainwater. It is therefore, necessary to explore ways of increasing water use efficiency in rain fed agricultural systems.

Climate variability has been identified as the major constraint to agricultural productivity in Sudan; and hence reducing the risk associated with climate variability has a high potential for increasing productivity in rain fed areas in the central clay plains of Sudan (Phillips et al., 1998).

Despite contributing a large share of the annual grain output, rain fed production of rain fed Sorghum in Sudan is largely unstable (Mhizha, 2010). The fluctuations echo in the availability of food in the country, often with a telling effect on the economy as high financial resources are to be channeled towards securing food security; which would deprived other economic sectors from development. The instability in rain fed production is largely credited to availability of rainwater, which itself shows wide spatial and temporal variability in both total amounts and distribution (Zinyengere, 2011). Rainfall variability, especially the less well defined onset of the rainy season has increased in the recent years past possibly linked to climate change. The start and end of the rainy season defines the length of the rainy season which strongly determines the success or failure of rain fed crops. In addition, the quality of the growing season, as indicated by the length and severity of within-season dry spells, will also influence the yield gap and can often cause total crop failure (Geerts et al., 2006; Phillips et al., 1998). While agricultural water management has largely succeeded in maximizing rainfall infiltration through soil and water conservation, the challenge of how to cope with dry-spells, short periods of water stress during crop growth, remains largely unsolved (Fox and Rockström, 2003). This because false planting dates requiring replanting are increasingly common in Rain fed areas (Raes et al., 2009).

There is an increasing demand for sowing strategies that minimize risk of total crop failure, such as staggered planting (FAO. 1997; Mpande and Tawanda, 1998). Such sowing strategies need to consider timing and lengths of crop phonological growth stages. This stem from the sensitivity of early growth stages (establishment phase) to increase in rain water and flooding of seedlings. In contrast, flowering stage is sensitive to water shortage where, in water deficient situations crop tends to shed its flowers.

Keeping view of the above, it is imperative to enhance the water productivity in agriculture. To accomplish this, there are broadly three options such as a) judicious management of rain water resources by determining and staggering sowing date and improve rain water use efficiency b) to improve productivity at the farm level through better management and use of improved varieties having drought resistance and higher yield potential and c) to optimize the use of land resources, and rain fed farming technologies All there can be achieved by using appropriate tools to predict water productivity under different rain fall a mounts and pattern or deficit water supply approaches for different crops. The complexity of crop responses to water shortage resulted in the use of empirical production functions as the most practical option to assess crop yield response to water. However, most of the current production functions are developed using regression equations are purely location specific and these black box models have limited applicability to different crops, locations and management practices. Therefore, use of physics based crop simulation models were preferred over the regression equations.

Crop models developed so far rely on the physics based concept of soil, plant water and climatic interactions and these models have been used by different researchers. Moreover, accurate modeling of crop response to water plays an important role in optimizing crop water productivity in agriculture (Geerts et al. 2009). There are a plethora of models that simulate the growth and development of cereal crops. As example The CERES-Maize (Crop Environment Resource Synthesis) model is a deterministic model designed to simulate maize growth, soil, water and temperature and nitrogen dynamics at a field scale. The input data required by most of these models are difficult to obtain or require detailed empirical measurements to establish hybrid-specific genetic coefficients as inputs to run the model and these can be suitably applied to the locations for which these are calibrated. Besides this, the models require more number of input parameters which is difficult to generate from field experiments and the crop growth engines are not water driven, i.e. separate module to account for crop growth responses under variable water supply situations is not available.

Keeping in view of these limitations, a crop water productivity model AQUACROP was developed by the Land and Water Division of FAO and released for use during 2009 (Steduto et al., 2009; Raes et al., 2009). AQUACROP is a water-driven crop model to simulate yield response to water of several herbaceous crops. It is designed to balance simplicity, accuracy and robustness, and is particularly suited to address conditions where water is a key limiting factor in crop production. The AQUACROP model has been parameterized and validated for simulating crops yield response to water (Hsiao et al. 2009; Heng et al. 2009). Although AQUACROP is based on complex crop physiological processes, it uses a relatively small number of explicit and mostly intuitive parameters with simplicity and accuracy (Steduto et al., 2009; Raes et al., 2009).

Some of the advantages of AQUACROP are: a) it is widely applicable with acceptable accuracy; b) it requires only commonly available input (i.e. climate, soil, and crop and field data); c) it allows easy verification of simulation results with simple field observations. In an attempt to compare performance of AQUACROP, CropSyst, and WOFOST Models, Todorovic et al. (2009) simulated sunflower (Helianthus annuus L.) growth under different water regimes in a Mediterranean environment. These three models differ in the level of complexity describing the crop development in the main growth modules driving the simulation of biomass growth, and in number of input parameters. AQUACROPis exclusively based on the water-driven growth module, in which the transpiration is converted into biomass through water productivity (WP) parameter. He recommended that under conditions of limited input information and yield predictions under variable water supply situations, the AQUACROP model should be preferred over other models and the use of simpler models should be encouraged.

1.2 Problem Definition

The fresh water resources worldwide are not infinite and this is clearly demonstrated in the limited Sudan share of river Nile water agreement where, through increased water withdrawals for the expansion of irrigated agricultural areas, rivers fail to irrigate all planned areas (Large Kenana, Rahad II, Wadi El Hawad and Marrawi extensions) i.e. closed basins. Typical issues in such closed basins are environmental degradation (water quality reduction, loss of biodiversity), declining ground water tables and aquifers, and deterioration of the ecological state of wetlands River discharges have dropped significantly in many basins, and insufficient water is available to meet the competing demands from various other users.

The production of food in rain fed agricultural systems; withdraw water from the system so that it is not available for later reuse. Water disappears into the air through evaporation from the surface and transpiration from plants. It is estimated that approximately 80% of the global evapotranspiration budget comes from rain fed areas, whereas the remaining 20% comes from irrigated agriculture. To supply water to rain fed fields for the evapotranspiration process; water is harvested from the rain. Excess water infiltrates the soil and mostly will be lost as runoff .It is thus essential to utilize every drop of rain water before it becomes runoff. To achieve this end it is believed that early crop sowing capture most of incoming rain water (Adam, 2008). Farmers in rain fed areas determine start of the growing season when rainfall water fill soil cracks but they are subject to the risk of probable short season of rain fall. However, in the context of a changing climate and variability in rainfall in particular, it not always secures to adopt early sowing date. It is thus essential to estimate the optimum sowing date and try to predict length of growing season based on the prediction of rain fall. This strategy is more popularly stated: to produce more crops per drop .The relationship between agricultural production and water consumption through evapotranspiration is complex. It is affected by crop characteristics and numerous growing conditions, such as climate, agronomic practices, soil type and fertility. Since the1900's the food production-water consumption relationship has been investigated by scientists from different backgrounds and with different interests. As a result of these different points of views by scientists or engineers, and the different scales of application, many definitions of water productivity exist in scientific publications.

In the beginning of the 20th century agricultural scientists from FAO started to look at the relationship between water use and dry matter production, evapotranspiration and rain fall. This is firstly documented in FAO paper 33(crop response to water, 199--), and lately, crop bio-mass is considered in their publication AQUACROP model, 2012). Conclusions were drawn by who assumed linear relations between cumulative dry matter production and cumulative evapotranspiration for most field crops However, this postulation is limited by the assumption that half of soil reservoir is filled with water. The linearity assumption needs to be evaluated in comparison to actual large scale data. This because field plot experiments proved to be quite unreliable since certain components of the water balance could not be determined at all, or could only be estimated roughly.

Increasing cereal crop yields and productivity to keep pace with vagaries of weather and increased future food demand is thus crucial for enhanced food security, incomes and livelihoods (Chauvin et al., 2012). Production of rain fed grain crops is projected to be negatively affected through projected higher and more variable temperatures, changes in rainfall patterns and increased occurrences of extreme events such as droughts and floods (Burke et al., 2006; Cooper et al. 2008). Current crop simulation models can be used to capture and quantify the effects of weather extremes, hence compounding on the already existing uncertainty regarding the direction and magnitude of climate change (White et al., 2011; Ramirez-Villegas et al., 2013) consequently our understanding of the impacts on crops and in the timing of crop adaptation strategies such as adjustments of planting dates and choice of crop cultivars Can be improved.

Despite the difficulty in predicting climate change impacts on crop production, mainly due to occurrence of extreme events, some studies e.g. Cooper et al. (2009) and Moore et al. (2012), clearly demonstrate the capacity of different scenarios generated from crop simulation models to explore the possible range of climate change impacts on crops. While some studies predict that sorghum will be worse affected by climate change and variability than other crops like wheat or rice mainly from increased atmospheric carbon dioxide (Schlenker& Lobell,2011; Wheeler & Kay, 2011), other studies indicate positive or contrasting results about the future yield response of sorghum(Srivastava et al., 2010; MacCarthy&Vlek, 2012). It is thus crucial to understand the uncertainty surrounding sorghum yield variability, but limited information exist in the clay plains of Sudan regarding the response of existing improved sorghum cultivars towards new climatic futures, considering that sorghum is one of the crops promoted under current climate variability and projected climate change.

1.3 Study Objectives

1.3.1 General Objectives:

This study was directed to examine sorghum crop yield response and identify the adaptation options in the sorghum based cropping system using simulation modeling. This requires calibration and validation of results of the crop simulation model and simulation of the impacts of future climate change scenarios on sorghum productivity. The second objective was to evaluate the performance of a set of adaptation options such as changes in sowing date.

1.3.2 Specific Objectives:

1. Benchmarking yield gaps in rain fed agriculture and assessment of long-term productivity in rain fed agriculture in Sudan.
2. To predict rain fed Sorghum crop grain yield at five regions representing different climate zones in Sudan in reference to prevailing climate conditions.
3. To study Seasonal Variability of Biomass Production for five different climate regions.
4. To study Rain fall water Use Efficiency (WUE) for regions of different climate element.

1.3 .3 Study Scope

The thesis is expanded in five chapters. The first chapter provides the background information regarding the problem faced justifications and problem impact and importance on country food security. On the basis of the impacts of climate change on crop productivity possible options to maximize benefit from rain water are explored for formulating food security policies. Consequently, the objectives of the research were defined.

Chapter 2 provides an overview of rain fed agriculture, sorghum crop, crop water demand, rain water supply, yield prediction schemes and impact of climate change.

Chapter 3 gives the materials and methods used in this study. It includes: Data Collection, study areas: Locations, characteristics, Input Data from each Study Areas, methods of data analysis and AQUACROP Yield Prediction Model.

Chapter 4 Is directed to study results obtained and discussions in relation to the study objectives and past research findings. In particular it covers: a) Benchmarking and simulation of Sorghum grain and biomass yield and water productivity in rain fed agriculture at different agro-climate zones in Sudan; b) To develop Sorghum crop sowing date management options for decision support at different climate zones in Sudan; c) To predict rain fed Sorghum crop yield (grain and biomass) at different climate zones in Sudan in reference to prevailing climate condition and in accordance with FAO criteria; d) o estimate impact of rainfall changes on Sorghum yield (Climate Change impact). In general this chapter is about the application of mathematical model to evaluate the proposed study objectives and the comparison of results with the reported ones.

Chapter 5 focuses on determining study summary, evaluation of conclusions drawn from the inferences of previous chapters and some outlook for the future in this field. Thereby, it covers recommendations for policy making and for future research.

CHAPTER TWO

Literature Review

2.1 Sudan Agricultural Resources

Climate in Sudan is the primary driver of the productivity and potential of the agriculture sector. While there is a vast land resource, much of the potential of this resource is climate constrained by the availability of water from rainfall and by temperature and evapotranspiration demand, as well as by availability of water resources inflows and by access to groundwater.

The climate of the Sudan ranges from arid in the north to tropical wet-and-dry in the far southwest. The contiguous Libyan and Nubian deserts of the north extend as far south as Khartoum and are barren except for small areas beside the Nile River and a few scattered oases. This gives way to the central steppes which cover the country between 15°N and 10°N, a region of short, coarse grass and bushes, turning to open savannah towards the south, largely flat to the east but rising to two large plateau in the west and south, Darfur (3,088 m) and JanubKordofan (500 m) respectively. South of the steppes is a vast shallow basin traversed by the White Nile, and the border with South Sudan? Temperatures do not vary greatly with the season at any location; the most significant climatic variables are rainfall and the length of the dry season.

Variations in the length of the dry season depend on which of two air flows predominates: dry northeasterly winds from the Arabian Peninsula or moist southwesterly winds from the Congo River basin. From January to March, the country is under the influence of the dry north-easterlies. There is practically no rainfall countrywide except for a small area in northwestern Sudan influenced by winds that have passed over the Mediterranean bringing occasional light rains. By early April, the moist south-west relies have reached southern Sudan, bringing heavy rains and thunderstorms. By July the moist air has reached Khartoum, and in August it extends to its usual northern limits around Abu Hamad, although in some years the humid air may even reach the Egyptian border. The flow becomes weaker as it spreads north. In September the dry north-easterlies begin to strengthen and by the end of December they cover the entire country. Khartoum has a three-month rainy season (July - September) with an annual average rainfall of 161 millimeters; Atbara receives showers in August that produce an annual average of only 74 millimeters. Temperatures are highest at the end of the dry season. The far south, however, with only a short dry season, has uniformly high temperatures throughout the year.

Northern Sudan, with its short rainy season, has hot daytime temperatures year round, except for winter months in the northwest where there is precipitation from the Mediterranean in January and February.

Conditions in highland areas are generally cooler, and the hot daytime temperatures during the dry season throughout central and northern Sudan fall rapidly after sunset. Most of Sudan's agriculture occurs in a fertile pocket between the Blue and White Niles which meet at Khartoum.

The system of rainfall over Sudan is complicated but in general the mean annual rainfall increases from zero in the extreme north of the country rising to 500 mm in central Sudan and increases to 700 or more the south (Figure 2.8). The duration of the rainfall (length of the rainy season in days) also increases from north to south. The coefficient of variability of rainfall decreases from north to south (>90% to less than 15%) so variability of annual rainfall is proportionally greater in the north than in the south.

2.2 Land:-

Sudan's total land area of 1,860,000 km2 (186 million hectares) approximately 140 million hectares2 (75%) have potential to support agriculture. Approximately 86 million hectares (45%) currently support some form of vegetative cover; 24 million hectares (13%) of rain-fed and irrigated agriculture and 62 million hectares (32%) of other vegetation (trees, shrub, herbaceous land cover - albeit sparse in some areas) utilized for pastoral livestock grazing and browsing of the 24 million hectares utilized for rain-fed and irrigated agriculture, approximately 14 million hectares are cropped annually. About 2 million hectares are under irrigation command, of which about 1 to 1.5 million hectares are estimated to be cropped annually. However, there is considerable variability of rain-fed cropped areas between years due to the high variability driven by rainfall, between years and between locations (temporal and spatially).

The water resources of Sudan include renewable surface water (rainfall and stream flow) and groundwater, both renewable and non-renewable. The total average annual renewable water resources are approximately 100 billion cubic meters (Bm3) per annum, of which 30.5 Bm3 are potentially available3 for use within Sudan.

Estimates of non-renewable groundwater resources vary widely between sources, but are large by comparison with renewable resources, and to date are largely undeveloped.

The surface water resources average annual volume is just over 98 Bm3, of which 96 Bm3 are inflows from cross border rivers, principally the Nile (94 Bm3) (98%) but also other rivers: Gash and Baraka in the east. The balance of surface water (2 Bm3) is generated internally from rainfall run-off. In some areas surface water runoff is captured with traditional water harvesting techniques in the rain-fed areas. Bigger scale use is made from the Gash and Tokar rivers in the east as well as in Khor Abu Habeel. A number of smaller scale projects are being implemented under the Water Harvesting Project and support specific rural communities. However, they are too small to contribute to the export of main commodities being targeted under this study. Surface flow in the main rivers White Nile, Blue Nile and Atbara River is used for major irrigation schemes. Under the 1959 Nile Waters Agreement Sudan is entitled to use 18.5 Bm3 annually. The irrigation sector is currently recording a total use of 14.4 Bm3 of this share. The remaining amount of 4.1 Bm3 is largely reserved for two major irrigation projects (Roseires -Dinder and Upper Atbara). There is further potential of up to 5 Bm3 (arising from the difference between historical average flows and the flows that were utilized for formulating the Nile Waters Agreement) which could be mobilized for Sudan in the long-term through various measures, which however may need to be agreed with other countries involved on the political level. While surface water availability is ultimately constrained, there is still potential for further development of irrigation use, which, dependent4 on crop type and location is in the range of 500,000 to one million hectares.

Groundwater potential in Sudan has been established in general terms. There is about 2 to 5 Bm3 of renewable groundwater5. There is also a significant non-renewable resource largely associated with the Nubian Sandstone Aquifer System (NSAS) estimated6 to be of the order of 600 Bm3. However, no detailed studies for e.g. quantity, recharge capacity and sustainable abstraction rates for project specific use have been performed to date.

2.3.1 Current and Potential Areas:

Sudan’s economy similar to most African nations relies heavily on its agriculture sectors. Agriculture represents roughly 80 percent of the work force. In 1996, agriculture accounted for 48 percent of the country GDP. In 2005, this number was reduced to 39 percent as the contribution of crude oil exports has steadily increased since Sudan began exporting this natural resource in 1999. Though the contribution to GDP has decreased by roughly 10 percent, the percentage of the population employed by agriculture has remained at 80 percent. Sudan also boasts the second largest animal population in Africa, which annually contributes substantially to the nation's GDP. Civil war has marred Sudan since 1983. Despite this, the country's wealth of natural resources (oil) has allowed for recent GDP growth of close to 7 percent. Even with recent economic success from crude oil exports,

Sudan's population has not shifted from being overwhelmingly agrarian, and remains largely dependent on rain-fed farms. Sudan faces several environmental issues. All but one has to do with water. Inadequate supplies of potable water, soil erosion, desertification, and periodic drought all plague Africa's largest country, and fifth largest population. It is estimated that a 50 to 200 km southward shift of the boundary between semi-desert and desert has occurred since first records were collected in the 1930s.4; whereas, an estimated 42 percent of the total area is considered cultivatable land, only 7 percent of that portion is actually cultivated.

2.3.2 Current Status:

Rain-fed food crops cover an area of 14 million ha and are predominantly based on sorghum and to a lesser extent sesame. Mechanized rain-fed farming is mostly confined to the east and central areas of the country whereas traditional farming is widely practiced. The rain-fed sector is an important contributor to Sudanese internal food security and produces 72% of sorghum, 100% of sesame and 68% of groundnuts grown in Sudan. Within the sector, mechanized farming produces 59% of sorghum, 45% of sesame and 7% of millet, which emphasizes the importance of the traditional sector.

The area of mechanized rain-fed farming has grown since 1970 and is still expanding, but productivity is very low and is declining. Most farms are operating at a loss and are at the same time impacting negatively on access to the rangelands. Smallholders are also operating at a loss if family labor is cost. Table(2.1) presents a summary of the current status of land resources and farming systems based on information from soils, land cover and farming systems, in total and for two rainfall ranges (less than 300 mm per and more than 300 mm per annum).

Rain-fed arable farming is largely only viable, financially and economically, in areas of rainfall greater than 300 mm per year, while irrigated farming is located in areas with access to surface water, principally the Nile, or with access to groundwater, mainly from shallow alluvial aquifers and/or the Nubian Sandstone Aquifer System. Approximately 75% of the total land area (140 million hectares) has soils classified with some potential for agriculture (though not all lands can be developed due to limitation of water availability (rain-fed and/or irrigation). Nearly 50% (88 million hectares) have some form of land cover, natural vegetation (64 million hectares) or arable farming (gross area of 24 million hectares).

The current arable farming systems are estimated to be about 16 million hectares (net cropped area per annum) of which irrigation is about 1 million hectares (out of a gross irrigation command area of 2 million ha) and rain-fed about 14.5 million hectares (out of a gross area of about 19 to 20 million hectares). The majority (95%) of the rain-fed farming is within the area experiencing rainfall greater than 300 mm per annum.

Table(2.1): Current Status of Land and Farming Systems:

Total		Rainfall Range	Area, million ha
	>300mm	<300mm	
186.71	60.18	126.53	Total Area
140.5	51.1	89.4	Soils of Agricultural potential
			Land cover
3.65	1.95	1.7	Irrigated
20.22	15.72	4.5	Rain-fed
63.78	41.43	22.35	Other Vegetation
87.65	59.1	28.55	Total
			Farming System
2.3	1.23	1.07	Irrigation. Cross
1	0.53	0.47	Net
20.22	15.72	4.5	Rain-fed Cross
14.38	13.66	0.72	Net
52.93	37.29	15.64	Pastoral
68.31	51.48	16.83	Total Farming Systems

Source: Task II – Sudan's Resources for Enhancing Food Security.

In addition to arable farming, pastoral livestock farming is practiced, based on grazing and browsing of extensive areas of natural vegetation or rangelands. These are (based on land cover survey) estimated to be of the order of 50 million hectares (based on assumed levels of use of vegetation). The total area of lands contributing to agriculture output is about 68 million hectares, of which rain-fed and irrigated farming are 21% and 2% respectively, and the balance (77%) pastoral livestock farming.

2.3.3 Farming System:

Table (2.2) presents a summary of a potential future scenario for land use in Sudan for the three main farming systems. It is based on a number of assumptions regarding development of farming systems and water resources including;

Irrigated agriculture: increase in efficiency of existing irrigation systems to increase cropping intensity (to 90%) and irrigated area to two million hectares. Expansion of new irrigation schemes with an irrigated areas of about 1.3 million hectares by allocation of surface water and groundwater resources, though the irrigated area may range from 0.9 to 2.6 million hectares dependent on the allocation of water resources and crop and irrigation system selection. The current scenario assumed utilization of 20 Bm3 of additional water from surface water (50%) and groundwater (50%) as discussed below:-

a) Increase in the cropping intensity of the existing rain-fed farmed areas (from 14.4 to 16.2 million hectares) through improved farming methods.
b) Expansion of the rain-fed farming areas by 6.8 million hectares in areas with rainfall greater than 300 mm per annum. However this area is nominal (based on 50% increase in cropped area within the rainfall range) and is dependent on land availability and soil suitability.
c) Contraction in the area of pastoral livestock farming with the expansion of new rain-fed farming (in the zone of rainfall greater than 300 mm), from about 37 to 30 million hectares (though there will be an increase in the volume of crop residues to partially offset the reduction in area).

The total renewable water resources available for use within Sudan are of the order of 30 Bm3, of which 27 Bm3 and 2 Bm3 are from surface water and groundwater respectively. In addition there are large reserves of non-renewable groundwater, mostly associated with the Nubian Sandstone Aquifer System. Current irrigation withdrawals are about 17 Bm3 per annum or about 60% of renewable resources. There is potential for expansion of irrigated agriculture through development of new lands with water supply from renewable surface water7 (approx. 10 Bm3) and groundwater, both renewable and non-renewable (for which it is proposed to allocate 10 Bm3 per annum). Based on the above scenarios net irrigated area would increase to about 3.4 million hectares, of which 1.3 million hectares are new irrigated lands (schemes). Rain-fed annual cropped area would increase from 15 to 23 million hectares (more than 50%), due to improved systems on existing farmed areas and new lands brought under cultivation. The area of pastoral livestock may decrease from 53 to 45 million hectares due to the expansion of rain-fed and irrigated farming. However the total area of farming systems would increase, due to conversion of non-farmed areas (bare soil) to irrigation, principally in zones with rainfall less than 300 mm per annum.

Table(2.2): Summary of Potential Farming Systems

Total		Rainfall Range	Area, million ha
	>300mm	<300mm	
			Irrigation-Net
2.07	1.11	0.96	Existing
1.3	0.69	0.61	New
3.37	1.8	1.57	Total Irrigated
			Rain-fed-Net
16.18	15.46	0.72	Existing
6.83	6.83		New
23.01	22.29	0.72	Total Rain-fed
46.02	29.81	16.21	Pastoral
69.03	52.1	16.93	Total Farming Systems

Source: Task II – Sudan’s Resources for Enhancing Food Security**.**

The areas of mechanized rain-fed farming can be increased (as can traditional areas), but without improvements in productivity there seems little point. Improvements in productivity in the mechanized sector point to the adoption of cultural techniques which will improve moisture management, timeliness of operations, use of purchased inputs, and better use of machinery. This translates into access to finance, provision and use of good quality seeds, planting in rows, access to sprayers of herbicides, the use of fertilizer, and combine harvesters. A further step would be the adoption of land preparation prior to the rains with the final improvement being the adoption of zero tillage. Plans to improve the traditional sector are based on improving access to credit, access to high quality seeds and more effective extension services. The last set of recommendations may sound mundane but agricultural research and development as well as extension have been neglected over the last ten years and have some catching up to do.

2.3.4 Production Current and Potential:

A comparison of current and potential future agricultural crop production is presented in Table 2.3. The current production is as reported for the irrigated and rain-fed farming systems, and the future production estimates are based on potential increases in cropped areas listed above and series of assumption on the preferred mix of crops. These assumptions include: for the increased irrigated area 35% is in wheat production, 5% in sugar cane, and the balance in oilseeds (30% sesame and 30% sunflower) and for rain-fed systems the increase in area is in oilseeds, shared equally between groundnuts, sunflower and sesame.

Overall annual production could be nearly triple from about 6.4 to 18.0 MMT. Production of wheat, if this is the focus of future development, would add 2.5 MMT to the existing 0.5 MMT production, and sugar production would add another 1.1 MMT. These additions would eliminate the need for sugar imports. Oilseed production would rise from 1.3 to 9.3 MMT. The above numbers include for an achieved increase of yields in all areas, and increased cropping intensity in the existing irrigation areas up to 90%.

While the approach is relatively simplistic (and is only one possibility of many used here for illustration) it shows the indicative magnitude of increases in production for the potential increase in cropped area. The actual increases will ultimately be dependent on the selected crops and to a large extent on the actual new developed areas, both irrigated and rain-fed, under future development programs.

Table(2.3): Current and Potential Production:

		Future Production (000 MT)			Current Production (000 MT)	Crops
Total	Rain-fad	Irrigated	Total	Rain-fad	Irrigated	
						Cereals
2,973	7	2,966	484	7	477	Wheat
3,115	2,252	863	3,115	2,252	863	Sorghum
671	667	4	671	667	4	Millet
6,759	2926	3,833	4270	2926	1344	Subtotal
						Oilseeds
2,944	2,661	283	873	590	283	Groundnut
3,969	1,450	2,519	99	69	30	Sunflower
2,429	1,360	1,069	326	324	2	Sesame
9,342	5,471	3,871	1,298	983	315	Subtotal
						Sugar
1,728		1,728	650		650	Rain fed sugar
						Fiber
175	12	163	175	12	163	Cotton
18,004	8,409	9,595	6,393	3921	2472	Total

Source: Task II – Sudan's Resources for Enhancing Food Security.

2.4 Water Resources:

The water resources of Sudan are renewable resources, comprising mainly the surface water of the Nile and its tributaries and renewable groundwater from surface water recharge as well as non-renewable groundwater resources principally of the Nubian Sandstone Aquifer System (NSAS).

The average annual total renewable water resources entering Sudan are just under 100 Bm3, of which about 87 Bm3 is from external inflows (Nile and other rivers), and the balance (12 Bm3) generated internally from rainfall. Under the 1959 Nile Waters Agreement25 the Nile flows (approx. 84 Bm3) 55.5 and 10 Bm3 are committed to downstream use in Egypt and for evaporative losses respectively, and the balance of 18.5 Bm3 for use within Sudan.

However, there are also varying estimates of the water resources, both surface water and groundwater, due in part to incomplete information and knowledge of the resources particularly groundwater, and in part to differing periods of surface water flows measurements. The approach taken for this report is to present a 'best estimate' of water resources, which is reasonably consistent between relevant sources. In doing so it is intended to provide an indication of the water availability as a foundation to determining the scale and extent of irrigated agriculture sub-sector. But it should be borne in mind, particularly for groundwater resources, estimates of water availability to sustain irrigated agriculture development need to be treated with some caution due to limited information on aquifer water levels, storage and yields. Only through monitoring and sustained pumping of these resources will there be greater certainty of its development potential.

2.4.1 Surface Water:

The surface water resources include the perennial flow of the Nile and its tributaries, as well as ephemeral seasonal flows (in the region generally referred to as 'spate' flows) within other catchments to the east and west of the Nile Basin, including the Gash and Baraka Rivers in the east and rivers and streams draining to the west and north. Surface water flows are also generated from internal run-off within Sudan (within the Nile Basin and other catchments) and from external cross-border river flows.

2.4.2 Nile River:

The Nile is one of the world’s longest rivers, traversing 6,695 kilometers from its headwaters in the Kagera Basin in Burundi to its delta in Egypt. The drainage area of the basin is about 3.2 million square kilometers across eleven countries; Burundi, Democratic Republic (DR) of the Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, South Sudan, Tanzania and Uganda. Despite its length and large catchment area, it has a relatively low annual flow of about 84 Billion cubic meters (Bm3)26 compared to other major rivers such as the Congo and Amazon (with average annual volumes of approximately 1,300 and 6,600 Bm3 respectively). This is due to a relatively low runoff coefficient (less than 5%) as a result of about 40% of the basin area contributing little or no run-off as it is comprises arid and hyper arid lands.

2.4.3 Nile Waters Agreement (1959):

Sharing of the Nile waters between Sudan and Egypt is stipulated through the 1959 Nile Waters Agreement. Sudan’s share under the agreement is limited to 18.5 Bm3 in an average year: 55.5 Bm3 is assigned to Egypt and 10 Bm3 for evaporative losses in both countries. The annual inflow to Sudan was estimated at 84 Bm3, based on pre-1959 records. Any increase in flow post agreement was to be shared equally between the two countries. In 2011 Sudan separated into two countries, Sudan (as part of the current study) and South Sudan. What was not clarified during the separation process was the status of the Nile Waters Agreement relevant to the two countries. This is likely to be the subject of future discussions and agreement the outcome of which is beyond the scope and intentions of this study to specify or on which to speculate. Therefore pending future developments for the purposes of this study it is assumed that the 1959 Nile Waters Agreement numbers are currently applicable.

Rainwater Harvesting: In addition to the construction of dams on the Nile, there are several projects for the harvesting of seasonal surface water run-off from ephemeral rivers and streams. These projects include structures for diversion of flows to local storage reservoirs (referred to as “hafirs”) and ponding areas for cultivation and livestock water supply. There are reportedly 500 such water harvesting projects nationally, with water harvesting estimated at between 3 and 15 Mm3 per annum.

The balance of the surface water resources is committed under the 1959 Nile Waters Agreement to downstream use in Egypt and for evaporative losses within both Egypt and Sudan.

The available surface water includes water from the Nile (balance between current withdrawals (14.4 Bm3), Nile Waters Agreement allocation (18.5 Bm3)) and share of additional Nile water above Agreement allocation levels estimated to be in the order of 5 Bm3 per annum.

2.4.4 Rain fed Agriculture :

For the purposes of the study rain-fed farming includes pastoral and arable farming methods. The former is largely based on the grazing of natural grasslands, predominantly savanna grasslands of the central and southern states, by both nomadic and sedentary pastoralists. Rain-fed arable farming is currently practiced as semi-mechanized farming, and to a lesser extent, as traditional hand and animal draft farming. The potential for rain-fed agriculture in Sudan was assessed and projects for its development identified, both in terms of production and post-production processing and marketing. This includes physical resources, farming systems, development projects, support services and supporting infrastructure development requirements.

2.5 Crop Production in Rain-fed Agricultural Lands :

Agriculture in Sudan is usually divided into three sectors: irrigated, semi-mechanized rain-fed and traditional rain-fed. The irrigated sector accounts for some 1.7 million ha and rain-fed food crops are produced from about 14 million ha of an estimated arable area of 19 million ha in the whole country. While the irrigated area is fairly stable the size of the rain-fed sector varies from year to year and the planted and harvested areas depend on the annual rainfall and distribution.

2.5.1 Climate: Rain-fed agriculture is generally confined to areas where the climate can be categorized as “semi-arid”, with mean annual rainfall of 300-600 mm in the north, and “dry monsoon” with mean rainfall of 600-850 mm in the south.

2.5.2 Cropping Pattern: The current cropping patterns are predominantly based on sorghum (grain and fodder production), and to a lesser extent sesame. However, current cropping patterns are to a large extent dictated by the farming systems, with low levels of inputs, lack of access to credit, poor support services (and as a consequence low productivity and returns), along with weak infrastructure and marketing constraints36 (as well as high taxes and weak sub-sector planning).

Mechanized or semi-mechanized rain-fed farming is mostly confined to Gedaref, Blue Nile, White Nile, Sennar and Kordofan states.37 It covers about 6 million hectares. Most consist of farm units of 1,000 or 1,500 feddans, although some farms are smaller. They are partly mechanized and depend on seasonal labor for some operations such as weeding and harvesting. On the other hand, there are other huge farms up to 250,000 feddans such as Agaadi. They are completely mechanized and use the most modern machinery and cultivation techniques.

Historically this subsector has been the source of sorghum exports as well as meeting domestic needs; however exports have now virtually ceased. In general the mechanized rain-fed farming is practiced on heavy clay soils, Vertisols, in areas where the rainfall varies between 400 and 800 mm per year. The area cropped annually varies with the rainfall. The main crops are sorghum and sesame. On a production basis mechanized farming accounts for about 42% of sorghum, 51% of sesame, and 10% of pearl millet. The main constraints in this sub-sector include poor infrastructure (in particular roads), poor untimely finance, poor services and a shortage of drinking water, which inhibits permanent settlement of farmers.

Traditional rain-fed farming is more widely practiced and the most vulnerable to crop failure due to poor rains or distribution. This sub-sector represents about 50% of cultivated land. Traditional farming is normally done on small holdings with manual farming operations, little or no external inputs and limited farmers' resources. The traditional sub-sector produces about 90% of pearl millet, 42% of sorghum, 46% of sesame and 68% of groundnuts. The sub-sector is largely confined to areas between the 350 mm and 800 mm isohyets for sorghum, cotton, and sesame, while pearl millet and groundnuts are grown on sandy soils receiving around 300 mm of precipitation annually. The sub-sector can be divided into millet and sorghum based cropping patterns. The millet pattern is dominant in the sandy soils of North and West Kordofan and Darfur states. Pearl millet is the preferred staple food, while groundnuts, sesame and roselle (karkade) are the main cash crops. The sorghum based pattern is dominant in the clay soils of South Kordofan, Blue Nile, White Nile, Gezira, Sennar and Kassala states. Sorghum is the main staple food, while sesame is the main cash crop. Other crops in the sector include maize, cassava, field water melon, cowpeas and other minor crops.

2.5.3 Sorghum Crop

Cereals dominate crop production in Sudan and provide nearly 53% of the population’s daily calorie requirements (FAO-SIFSIA. 2012). The same high levels of annual fluctuation as for other crops characterize the production of the major staples – sorghum, millet and wheat. Before 1960, apart from small areas in Darfur and Kordofan, Sudan grew wheat only in the northern state, and even there only on limited scale. Although environmental and climatic conditions are less favorable for wheat than in the north, the government decided to grow wheat on the Gezira Scheme, between the White and Blue Niles south of Khartoum, because of a local land shortage and high cost of irrigation water in the north. At the same time, wheat cultivation was extended to the New Halfa Agricultural Production Scheme in the east, on the Atbara River (FAO 2000).

During the agricultural seasons in 2000–05, about 1.89 million ha of arable land were under irrigated agriculture, 8.37 million ha under traditional rain-fed cultivation and 5.44 million ha under mechanized farming In 2006, more areas were added to all these three sectors because of favorable rains. Despite a few outbreaks of pests or diseases, the 2006–07 seasons produced a record cereals harvest of 6.64 million metric tons. These yields were 22 per cent higher than in 2005, and production across all three sectors was considerably improved: 36 per cent higher than the previous year’s average and above the long-term average .

The production of cereals, sorghum, millet and wheat declined in 2010 by nearly 42% from an average of 4.9 million metric tons in 2006-09 to only 2.9million metric tons. The magnitude of production decline varied by crop: 46.8per cent for sorghum; 31.3 per cent for wheat; and 24.2 per cent for millet. The largest production decrease occurred in the mechanized rain-fed farms, which contributed nearly 32 per cent of national cereals output (FAO-SIFSIA. 2012).

Sorghum is Sudan’s principal cereal crop, usually accounting for between 70 and 80% of the country’s annual cereal production and about 50% of its annual cereal consumption. It may be sown under rain-fed conditions any time between the first rains in June until late August or even as late as early September. Sowing in the semi-mechanized rain-fed sector can be delayed by the difficulty of using machinery on the land when the first rains have been excessive. Harvesting usually starts in October with the early-sown crop and may continue into January. Under irrigation the crop is usually sown in July. A number of varieties and landraces are available to farmers, such as Feterita, Wad Ahmed, Alkamoy, Muged and Tabet, each with its own characteristics of color, taste, marketability, and suitability to climatic and moisture conditions.

Crop production from traditional rain-fed farming has grown since the early 1990s; it has surpassed the level of semi-mechanized farming, which shrank during the same period. Semi-mechanized system has ceased to be the dominant source of food (sorghum) for Sudan (Institute for Security Studies2005). However, the contribution of the irrigated sector has remained relatively stagnant, apart from its surge in production in response to drought and locusts attacks in 2001–02, and again in 2006–07 when wheat prices increased. However, this production system clearly has the capacity to make a major contribution to food production as a result of increased harvested area (Institute for Security Studies 2005).

Sudan’s total cereals production is usually sufficient to meet domestic needs, especially in terms of sorghum and millet, but is a net importer of wheat (Ahmed, 2010). Generally speaking, in terms of availability of arable land and different water resources, the country has the potential to become the main food provider for Africa and the Middle East. Over the past few decades, however, variability of rain, seasons of severe drought, problems with food distribution and civil war, and above all mismanagement and lack of knowledge have left the country with recurring food shortages Sudan´s agricultural exports can be divided into three categories: (i) field crops (e.g. cotton, sesame, peanuts, sugar); (ii) livestock (e.g. sheep, camels and cattle); and (iii) gum Arabic, which represents the major forest exports These exports were the main source of foreign currency until the late 1990s when oil replaced them. From that time until the secession of South Sudan, the country turned from an agricultural to a petroleum exporter, following the unprecedented boom of its petroleum export revenues.

The trade balance for the fiscal year ending September 2000 achieved are mark able improvement, with a surplus of US$226.2 million that was directly attributed to the introduction of oil exports, as well as the reform of economic policies geared towards encouraging exports (Institute for Security Studies 2005).Meanwhile, agriculture showed a dramatic deterioration in its contribution to the country's exports, falling to 8% in 2006 and to 3% in 2007, down from an average of 74% in the 1996-98 periods Both the relative share and absolute value of agricultural exports have declined Agriculture has a significant role to play in the country's development, in terms of exports as well as industrialization – for example, as an incubator for major manufacturing industries such as edible oils, leather, and sugar Nevertheless, it remains the cause of the country´s most serious environmental problems. These include: (i) land degradation (e.g. riverbank erosion); (ii) the emergence of invasive species; (iii) use and mismanagement of pesticides and other agro-chemicals; (iv) water pollution (UNEP 2007); (v) the spread of malaria; and (v) the introduction of perfect conditions for water-borne diseases such as bilharzias (Ali Ayoub).

2.6 Crop Water Demand and Supply

Evapotranspiration is the combination of soil evaporation and crop transpiration. Weather parameters, crop characteristics, management and environmental aspects affect evapotranspiration. The evapotranspiration rate from a reference surface is called the reference evapotranspiration and is denoted as ETo. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference grass crop completely covers the soil, is kept short, well watered and is actively growing under optimal agronomic conditions.

The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiration surface, soil factors do not affect ETo. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. ETo values measured or calculated at different locations or in different seasons are comparable as they refer to the evapotranspiration from the same reference surface. The only factors affecting ETo are climatic parameters. Consequently, ETo is a climatic parameter and can be computed from weather data. ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen et al., 1998).

Owing to the difficulty of obtaining accurate field measurements, ETo is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing reference evapotranspiration from meteorological data. Numerous researchers have analyzed the performance of the various calculation methods for different locations. As a result of an Expert Consultation held in May 1990, the FAO

Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration ETo.

2.7 Methods to Estimate ETo

Many investigators have developed equations of reference evapotranspiration. The following commonly used reference evapotranspiration models were selected for the calculation of crop evapotranspiration (Water requirement of the crop).

Penman-Monteith FAO-56 Model: Penman (1948) did not include a surface resistance function for water vapor transfer. For practical applications, he proposed an empirical equation for the wind function. The combination equation with aerodynamic and surface resistance term is called the Penman-Monteith equation consultation of experts and researchers was organized by FAO in May 1990, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advice on the revision and update of procedures.

The panel of experts recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculation of the various parameters. By defining the reference crop as a hypothetical crop with an assumed height

of 0.12 m having a surface resistance of 70 s m-1 and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide. The FAO Penman-Monteith method to estimate ETo can be derived:

$$ET_{\circ}=0.408\Delta(Rn-G)+\gamma\ 900\ /T+273\ u2\ (es-ea)\ /\Delta+\gamma(1+0.34\ u2)\text{-------------}(2.1)$$

Where:

ETo :reference evapotranspiration (mm day-1),

Rn :net radiation at the crop surface (MJ m-2 day-1),

G : soil heat flux density (MJ m-2 day-1),

T :mean daily air temperature at 2 m height (°C),

u2 :wind speed at 2 m height (m s-1) .

es :saturation vapour pressure (kPa) .

ea :actual vapour pressure (kPa) .

es – ea:saturationvapour pressure deficit (kPa) .

slopevapour pressure curve (kPa °C-1) .

psychometric constant (kPa °C-1) .

The equation uses standard climatologically records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m above an extensive surface of green grass, shading the ground and not short of water. No weather-based evapotranspiration equation can be expected to predict evapotranspiration perfectly under every climatic situation due to simplification in formulation and errors in data measurement. It is probable that precision instruments under excellent environmental and biological management conditions will show the FAO Penman-Monteith equation to deviate at times from true measurements of grass ETo. However, the Expert Consultation agreed to use the hypothetical reference definition of the FAO Penman-Monteith equation as the definition for grass ETo when deriving and expressing crop coefficients.

2.8 Estimation of Crop Water Requirement

The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. By using the FAO Penman-Monteith definition for ETo, one may calculate crop coefficients at research sites by relating the measured crop evapotranspiration (ETc) with the calculated ETo, i.e., Kc = ETc/ETo. In the crop coefficient approach, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for within the crop coefficient. The Kc factor serves as an aggregation of the physical and physiological differences between crops and the reference definition.

2.9 Rain Water Supply

Rainfall is the only source of water for production in the rain-fed sector for crop production as well as for rangelands and pasture. The climate in Sudan produces a shorter rainy season in the summer while the rest of the year is almost dry. In general rainfall reduces from south to north, from around 700 mm to almost zero in the Sahara desert. The length of the rainy period also reduces from south to north, from 6 months in the south to couple of days in the north. Rain-fed agriculture is usually practiced in areas receiving at least 300 to 400 mm annual rainfall in the long-term average. The two key factors of “Sudan’s Resources for Enhancing Food Security” .are land and water.

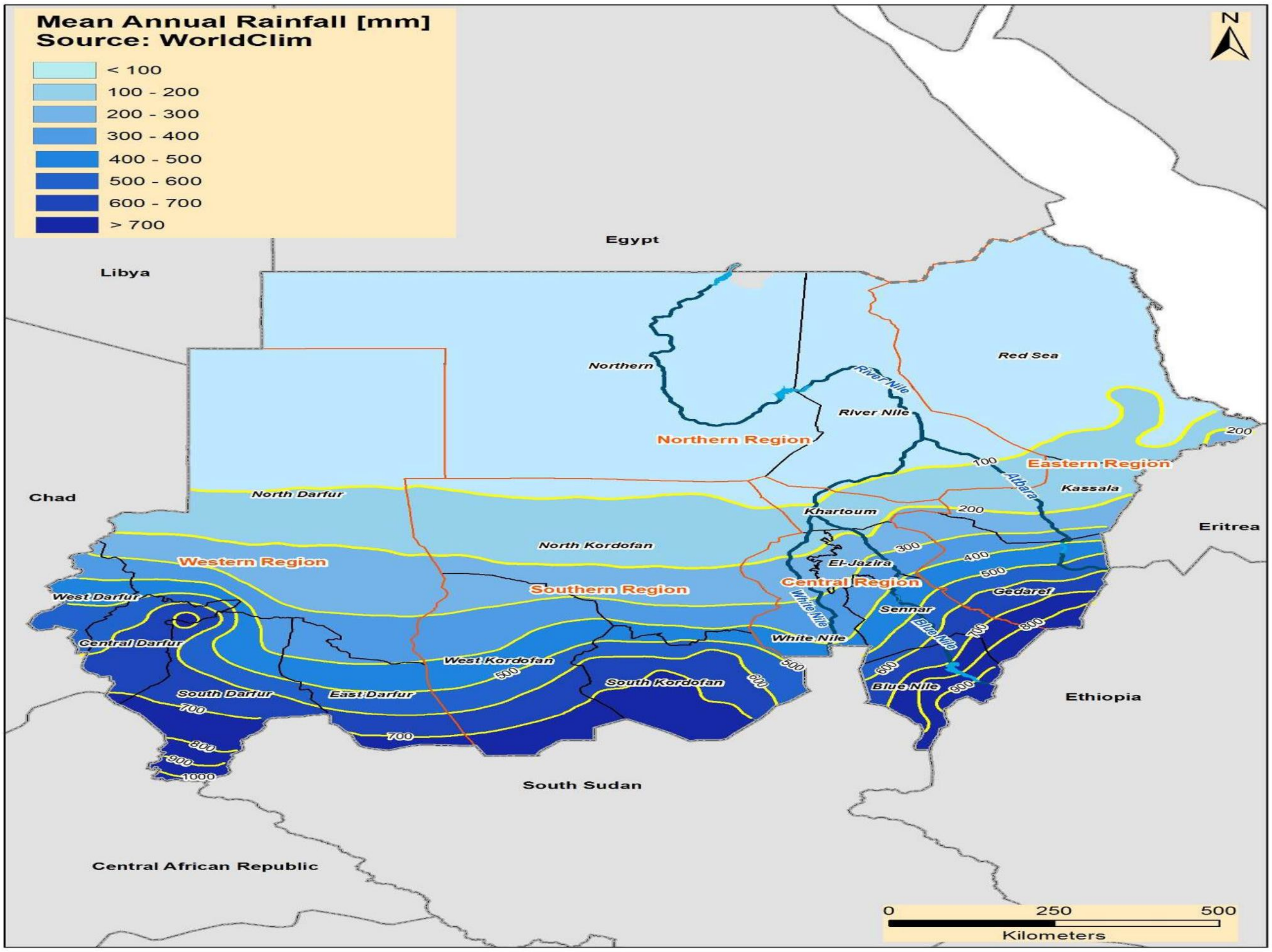


Figure (2.1): Rainfall Map of Sudan

2.10 Yield Prediction :-

The complexity of crop responses to water deficits led earlier investigations to the use of empirical production functions as the most practical option to assess crop yield as related to water. Among the methods based on this approach, FAO Irrigation & Drainage Paper no. 33, Yield Response to Water (Doorenbos and Kassam, 1979) stands out. For decades, this paper has been widely adopted and used to estimate yield response to water of numerous crops, particularly by planners, economists, and engineers (e.g., Vaux and Pruitt, 1983; Howell et al., 1990). Other software developed by FAO, such as the irrigation scheduling model CROPWAT (Smith, 1992), uses this approach to simulate water-limited yield. Central to the approach is the following equation, relating yield to water consumed:

$$[(Yx- Ya)/ Yx] = Ky [((ETx- Eta)/ ETx)] \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{[2.2]}$$

WhereYx and Ya are the maximum and actual yield, ETx and ETa are the maximum and actual evapotranspiration, and Ky is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. Understanding of soil–water–yield relations has improved markedly since 1979; this, along with the strong demand for improving water productivity as a means to cope with water scarcity, prompted FAO to reassess and restructure its Paper no. 33. This was done through consultation with experts from major scientific and academic institutions and governmental organizations worldwide. The consultation led to the decision of developing a simulation model for field and vegetable crops that would evolve from Eq.(2.2), to remain water-driven and retain the original capacity of Paper no. 33 for broad-spectrum applications, and at the same time achieve significant improvements in accuracy while maintaining adequate simplicity and robustness. At the start, the main existing crop models were evaluated since many of them already could simulate yield response to water. These models, however, presented substantial complexity for the majority of targeted users, such as extension personnel, water user associations, consulting engineers, irrigation and farm managers, and economists. Furthermore, they required an extended number of variables and input parameters not easily available for the diverse range of crops and sites around the world. Usually, these variables are much more familiar to scientists than to end users (e.g., LAI or leaf water potential). Lastly, the insufficient transparency and simplicity of model structure for the end user are considered a strong constraint.

To address all these concerns, and in trying to achieve an optimum balance between accuracy, simplicity, and robustness, a new crop model, named Aqua Crop, has been developed by FAO. The conceptual framework, underlying principles, and distinctive components and features of Aqua Crop are herein described, while in companion papers of this symposium the structural details and algorithms are reported by Raes et al. (2009) and the calibration and performance evaluation for several crops are presented by others.

2.11 Crop growth Simulation Models

Models are generally defined as simplification or abstraction of a real system . This is particularly the case for models of biological systems like crops, where the reality is composed of a vast number of components and processes interacting over a wide range of organizational levels . Specifically, a crop model can be described as a quantitative scheme for predicting the growth, development, and yield of a crop, given a set of genetic features and relevant environmental variables. Crop models can be useful for different purposes; primarily, crop models interpret experimental results and work as agronomic research tools for research knowledge synthesis. Lengthy and expensive field experiments, especially with a high number of treatments, can be pre-evaluated through a well-proven model to sharpen the field tests and to lower their overall costs. Another application of crop models is to use them as decision support tools for system management. Optimum management practices, either strategic or tactic, such as planting date, cultivar selection, fertilization, or water and pesticides usage, can be a assess through proven models for making seasonal or within-season decisions (Boote et al., 1996). Other uses, such as planning and policy analysis, can benefit from modeling as well.

Efforts in crop simulation modeling, aimed primarily at the integration of physiological knowledge, were started in the late 1960s by several research groups; among them that of de Wit and co-workers Subsequent efforts led to the development of more advanced models, some of them more oriented toward the single-plant scale, such as CERES and others more oriented toward canopy-level scale and as management tools to assist in decision making, such as EPIC its derivation ALMANAC, CropSyst the DSSAT cropping system model (Jones et al., 1987), the Wageningen models and the APSIM models (Keating et al., 1995). Scientists, graduate students, and advanced users in highly commercial farming represent the typical users of these models,

Depending on the purpose and objectives of the crop model, we can distinguish two main modeling approaches: scientific and engineering. The first mainly aims at improving our understanding of crop behavior, its physiology, and its responses to environmental changes. The second attempts to provide sound management advice to farmers or predictions to policymakers. Scientific modeling is also meant to be more mechanistic, based on laws and theory on how the system functions, while engineering modeling is meant to be functional, based on a mixture of well-established theory and robust empirical relationships, as termed by Crop growth simulation models have become widely accepted tools for assessing the impact of climate change on crop production. These models need for their simulations, multivariate weather series representing present and future climates to simulate crop growth on a daily time step (Mearns et al., 1997). Crop producers need to adapt to climate change through changes in farming practices, cropping patterns, and use of modern technology.

Researchers use crop models to guide farmers to make crop management decisions such as selection of suitable crops, crop varieties, sowing dates and irrigation scheduling to minimize the risks associated with climate change. The expected future changes in climatic conditions namely solar radiation, air temperature, precipitation and higher concentration of carbon dioxide (CO2) can be analyzed by using crop models ZINYENGERE et al., 2011). It has been observed that CO2 concentration showed a marked increase in the last century mainly due to human activities (IPCC, 2007) and atmospheric models predict that if industries continue to utilize fossil fuels, the levels of CO2 will double in the near future. There is wide spread uncertainty regarding the physiological response of crops to enriched carbon dioxide in the atmosphere. Some researchers argue that the expected carbon dioxide enrichment could be beneficial to some crops. Easterling and Mearns, L. O.. (1998) report that exposure of C3 plants to elevate CO2 generally results in stimulated photosynthesis and enhanced growth. As discussed by Long et al. (2006), crops sense and respond directly to rising atmospheric CO2 concentration through photosynthesis and stomata conductance and this is the basis of the fertilization effect on yield. Evidence has also been found that increased atmospheric carbon dioxide concentration may lead to increased crop productivity, in particular for

C3 plants (e.g. Kinball et al., 1995). In China for example, Xiong et al. (2007) used the Crop.

2.12 Governing Equations and Concepts of FAO AQUACROP Model

AQUACROP model is based on the crop growth engine which is basically water driven, in which, the crop growth and production are driven by the amount of water used through consumptive use of the plant. Among the empirical function approaches, FAO Irrigation & Drainage Paper n. 33 (Doorenbos and Kassam, 1979) represented an important source to determine the yield response to water of field, vegetable and tree crops, There was a constant scientific and experimental progress in crop-water relations from 1979 till date, which led to a revision framework that treats separately field crops from tree crops. For the field crops, it was suggested to develop a model of proper Structure and conceptualization that would evolve from (Eq 2.2) and be designed for planning, management and scenario simulations. The result is the AQUACROP model which differs from the main existing models for its balance between accuracy, simplicity and robustness.

AQUACROP is FAO's crop water productivity simulation model. AQUACROP evolves from the previous Doorenbos and Kassam (1979) approach (Eq.2.3) by separating (i) the ET into soil evaporation(E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index . (HI) The separation of ET into E and Tr avoids the confusing effect of the non-productive consumptive use of water (E), especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI and also avoids the confusing effects of water stress on B and on HI. The changes led to the following equation for the AQUACROP model .

$$B = WP \times \sum Tr \quad \text{……………………………………………………. (2.3)}$$

Where, Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m2 and per mm of cumulated water transpired over the time period in which the biomass is produced). The main change from Eq. 1 to AQUACROP is in the time scale used for each one. In the case of Eq. 1, the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. 2 the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits.

2.12.1 Advantage of AQUACROP Over Other Crop growth Simulation Models

- Canopy development expressed as canopy cover (CC) of the ground and not through leaf area index (LAI) This offers a significant simplification in the simulation by reducing canopy development with time to a sigmoid function using a canopy growth coefficient. Senescence of the canopy is simulated with a decline function .

- Root development is expressed in terms of effective rooting depth as a function of time. A functional relationship is also established between roots and shoots development .

- Biomass (B) is calculated using WP and Tr. WP is normalized for climate (atmospheric evaporative demand and carbon dioxide) so that it can be used in different climatic zones in space and time. WP is also partially affected by fertility levels .

- Yield (Y) is calculated as the product of B and HI. HI increases mostly linearly with time, starting after pollination and until near physiological maturity.

- Water stress is expressed through stress coefficients (Ks) specific of each basic growth expression. These are canopy expansion, stomata control of transpiration (gs), canopy senescence and harvest index.
- AQUACROP uses a relatively small number of explicit and mostly-intuitive parameters and input variables.

2.13 Climate Change

Climate change is now a reality and not a hypothesis and will most likely have negative impacts on both agricultural and socio-economic development in the Sudan (Adam, 2015). Increased frequency of climate anormalizes or adverse trends, as predicted by most climate change scenarios, may translate quickly into regional or local calamities, particularly in the Sudan savannahs.

Evidence of climate change can be seen in displacement of the 40 mm and 100 mm isohyets to the south and the disappearance of 1,200-mm isohyets from Sudan Both the onset date and duration of the rainy season vary considerably among years, involving considerable uncertainty for agriculture. The use of genotypes that can fit into variable lengths of growing season as well as synchronize their maturity time with the end of the season could well increase ability to cope with this trend. In Sudan, the length of growing season has decreased since the severe droughts of the 1970s, requiring farmers to help themselves with either technologies they possess or options that may be provided by development projects.

Climate change contributes to increase the uncertainty on crops yield, promoting the development of crop simulation models for yield assessment. Improved understanding of the potential effects of climate change on crop yields would provide an excellent tool for planning, management, research and policy decisions, being also a useful tool for technicians and farmers (White et al., 2011). Models to predict the effects of climate change are needed because it is rarely possible to perform controlled experiments where one or two factors are changed while others are held constant, particularly for the time scales and spatial scales of interest. One cannot measure, for example, global crop production with climate change and compare it to a world without. Instead, one must perform the controlled experiments in the simplified world of computer models, which can be run at any scale. Analysts aiming to monitor the effects of climate change on crop yield must rely on some conceptual or numerical model of how crop yields respond to climate .

A commonly used approach to this prediction problem is based on numerical models that simulate the main processes of crop growth and development. These process-based models, also known as “crop models” or “simulation models”, attempt to encapsulate the best-available knowledge on plant physiology, agronomy, soil science and agro meteorology in order to predict how a plant will grow under specific environmental conditions. The models are “eco physiological” because they use mathematical descriptions of physiological, chemical and physical processes to simulate crop growth and development over time. Physiological processes considered may include photosynthesis, respiration, growth and partitioning, development of reproductive structures, transpiration, and uptake of water and nutrients. Chemical and physical processes can involve soil chemical transformations, energy flows, and diffusion of gases into and out of leaves, among others.

Predicting crop growth using eco-physiological models requires some initial conditions to be specified, such as the soil nutrient and water status, the planting date and density. Data on temperature, solar radiation, precipitation, or other weather parameters are then used to estimate how the development and growth of the crop progress over the cropping season. Most models operate at daily time steps, starting at planting and ending at the prediction of harvest or physiological maturity, depending on the crop. Information on irrigations, fertilizer applications, tillage events, pests, diseases, or other factors also may be considered.

Fig.2.2 represents the main loop of hypothetical eco-physiological model through a series of subroutines that estimate plant or soil processes on an hourly or daily basis, outputting intermediate values at specified intervals. In each cycle, the model checks whether the crop has reached maturity or a harvest data, in which case the yield and a diverse range of summary data may be output.

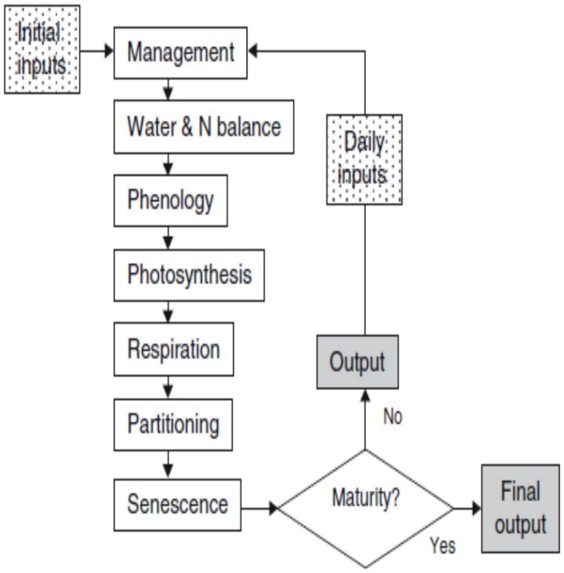


Fig (2.2) Flow diagram for a hypothetical eco-physiological model with a daily time step.

Yet these models also require extensive input data on cultivar, management, and soil conditions that are unavailable in many parts of the world. More significantly, even in the presence of such data these models can be very difficult to calibrate because of a large numbers of uncertain parameters. Often this parameter uncertainty is ignored and a subjective decision is made to proceed with a single set of parameter values that produces acceptable agreement with observations. When uncertainties in parameter values are explicitly considered, however, the uncertainty estimates for model projections can widen substantially.

An alternative to this process-based approach is to rely on the statistical models, in which historical data on crop yields and weather are used to calibrate relatively simple regression equations. It should be clear that purely statistical approaches, whether based on time series or cross-sectional data, are not inherently better or worse than more process-based approaches. There are some advantages, such as limited data requirements and the potential to capture effects of processes that are relatively poorly understood, such as pest dynamics, as well as some disadvantages, such as difficulty in extrapolating beyond historical extremes. On the other hand, statistical approaches cannot proceed successfully without some consideration of the underlying processes, for example the choice of which months of weather to consider will depend on the growing season of the crop, and the choice of what climate variables to use will depend on the processes thought to be most important. (Lobell, and Schlenker, 2011). It should be noted that the distinction between “process-based” and “statistical” models is somewhat arbitrary. All process-based models have some level of empiricism, and all statistical models have some underlying assumptions about processes.

Time series based models have been widely used to evaluate the impacts of climate variability and change on crop production. They are particularly useful in situations where there is insufficient data to calibrate more process-based models, and where detailed spatial datasets are not available, both of which are accurate descriptions of the situation in many developing countries. Their main requirement is the availability of sufficiently long time series (at least 20 years) of both weather and crop harvests (Lobell, et al., 2011). A time series of crop yield may be divided into three components; the mean yield, the trend in yield with time, and the residual variation. The mean yield is determined by the interacting effects of climate, soil, management, technological and economic factors. The trend is probably mainly due to long-term economic and/or technological changes. The third component is the variation between years and it is a prime objective of agricultural meteorologist to understand the role of weather in this variation. Uncertainty in weather creates a risky environment for agricultural production. Crop models that use weather data in simulating crop yields have the potential for being used to assess the risk of producing a given crop in a particular environment and assisting in management decisions that anticipate appropriate measures.

CHAPTER THREE

MATERIALS AND METHODS

3.1 The Study Area

The study data was collected from five meteorological stations to represent five different agro ecological zones located in the north, middle and south of the country (Table 3.1 and 3.2). Daily Climate Data (Rain fall, humidity, wind speed, sun shine hours, and max and min temperature) and Sorghum crop yield was collected from the five climatic regions (El Dalang, El damazine , El Gedarif, El obied, and El fashir) For the period of 1983 to 2013.

Table (3.1): Characteristics of the regions used in the study :

Station	Region	Coordinates	Elevation	Humidity (%)	Min. Temp. (C°)	Max (c°)	Annual Rainfall (mm)	Sunshine Duration (hours)	Wind Speed (km/d)
El Dalang	Semi arid	N12.15 E29.76	688 m	44.1	20.8	35.3	680.6	8.3	225.3
El Gedarif	Semi arid	N14.03 E35.38	634 m	42.4	21.4	36.8	612.0	9.1	231.7
Edamazine	sub-humid	N11.76 E34.35	475 m	47.7	20.7	35.8	698.2	8.1	218.8
Elobied	Arid	N13.14 E30.13	568 m	34.6	20.0	34.7	329.0	9.2	312.2
Elfashir	Arid	N 13.62 E25.35	700 m	31.2	17.2	34.7	193.3	9.3	180.2

Source: Task II – Sudan's Resources for Enhancing Food Security.

Table(3.2):Sudan cereal production parameters, thirty-years Average.

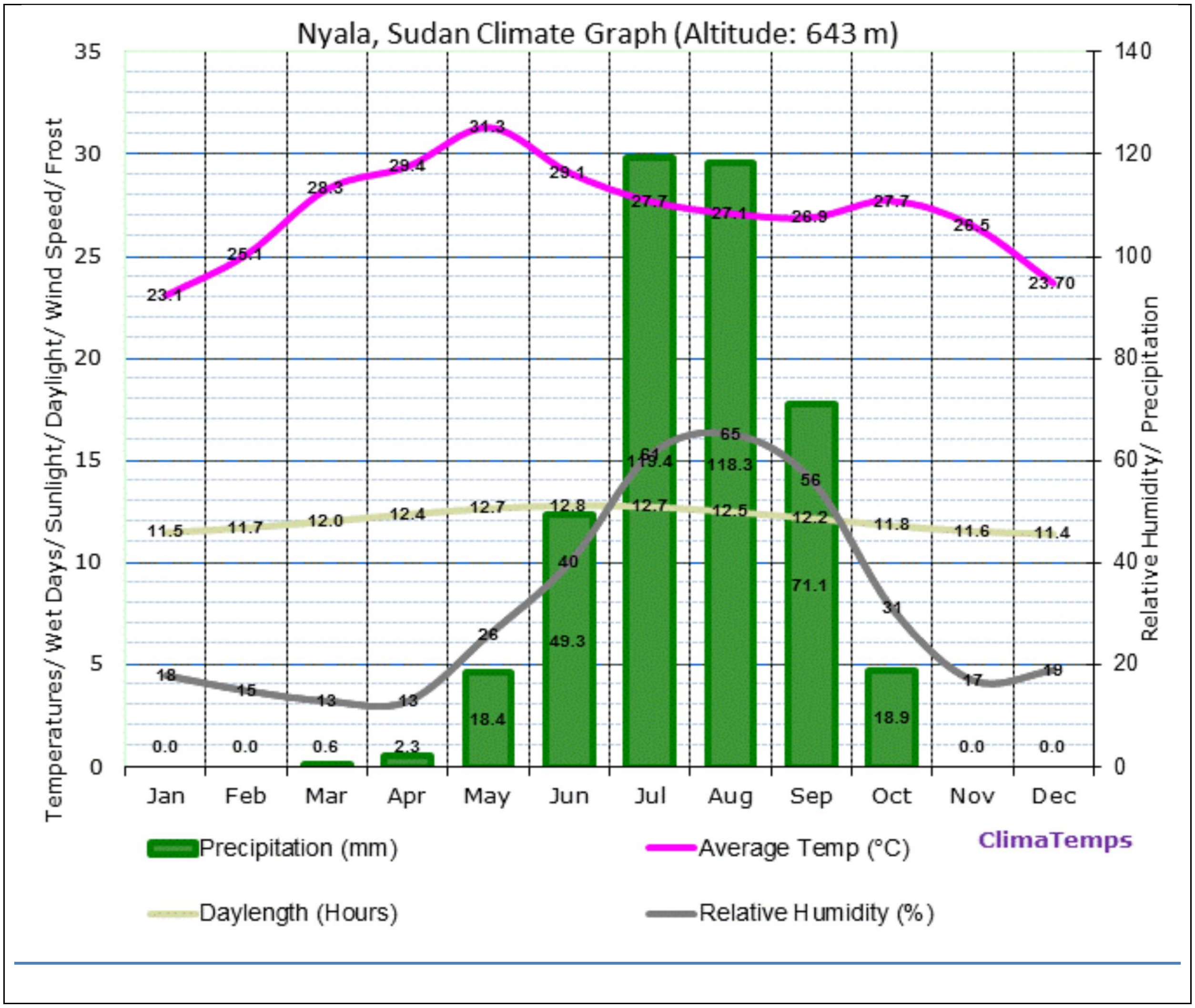
	Sorghum		
State/Scheme	Area*000 ha	Yield/.t/ha	Prodn.000 t
Irrigated sector			
Northern	5	2.6	13
River Nile	18	2.3	40
Khartoum	0	0	0
Suki	13	2.2	29
Sennar	30	1.8	53
White Nile	43	1.8	75
Gezira	199	2.1	420
Rahad	38	2.1	80
New Halfa	31	2.1	65
Gash	26	2.3	61
Tokar	5	1	5
Kassala	0	1.6	1
North Kordofan	2	1.3	2
Total Irrigated	410	23.2	844
Semi-mechanized Rain-fed Sector			
Kassala	268	0.5	131
Gedaref	1491	0.4	650
Blue Nile	261	0.4	110
Sennar	598	0.4	222
White Nile	337	0.4	131
North Kordofan	8	0.4	3
West Kordofan	0	0	0
South Kordofan	287	0.4	119
Total SMRS	3250	2.9	1366
Traditional			
Khartoum	25	0.4	11
Gezira	254	0.4	107
Blue Nile	55	0.6	31
Sennar	149	0.4	67
White Nile	161	0.5	84
Kassala	100	0.4	38
River Nile	27	0.9	23
Red Sea	10	0.6	6
North Kordofan	405	0.2	91
West Kordofan	0	0	0
South Kordofan	312	0.7	204
North Darfur	84	0.3	24
South Darfur	399	0.5	208
West Darfur	147	0.7	98
Total Traditional	2128	0.5	992
Total Sudan	5788	7.1	2358

Source:MAI,FAO.crop and food security assessment mission 2014.

The irrigated sector accounts for a relatively small proportion of the area under sorghum - 7% in the period 2008/09 – 2012/13 (Table 4.2) - but yields, at more than 2 t/ha, are usually four to five times greater than those achieved under rain-fed conditions. Consequently, from 7% of the total area under sorghum during that 5-year period, 26% of the country’s sorghum was produced. Almost half of Sudan’s irrigated sorghum production comes from the Gezira Scheme.

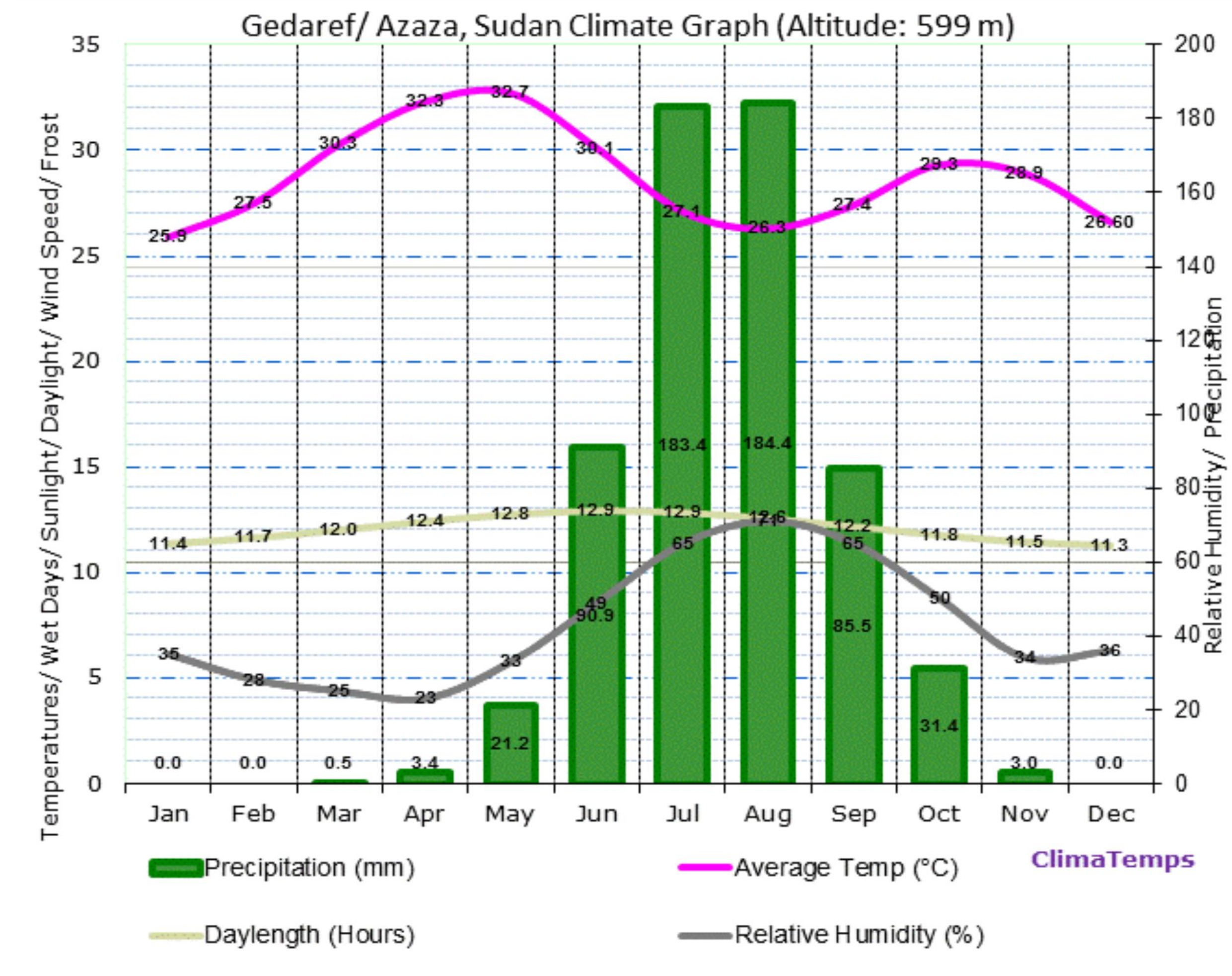
According to Emberger method, Eldmazine belong to the sub-humid class. El-Gedarif is classified as semi-arid and the remaining stations are classified as arid. The semi-arid zone can be represented by the climate data of, Nyala, Abu Naama (Umm Benin) , Gedaref and El Obeid (Figures 3.1, 3.2,3.3) consequently . The Dry Monsoon zone can be represented by the climate data of Damazin and El Dalang (Figure 3.4,3.5) consequently.

Rain-fed agriculture is generally confined to areas where the climate can be categorized as “semi-arid”, with mean annual rainfall of 300-600 mm in the north, and “dry monsoon” with mean rainfall of 600-850 mm in the south.



Source: Task II – Sudan's Resources for Enhancing Food Security.

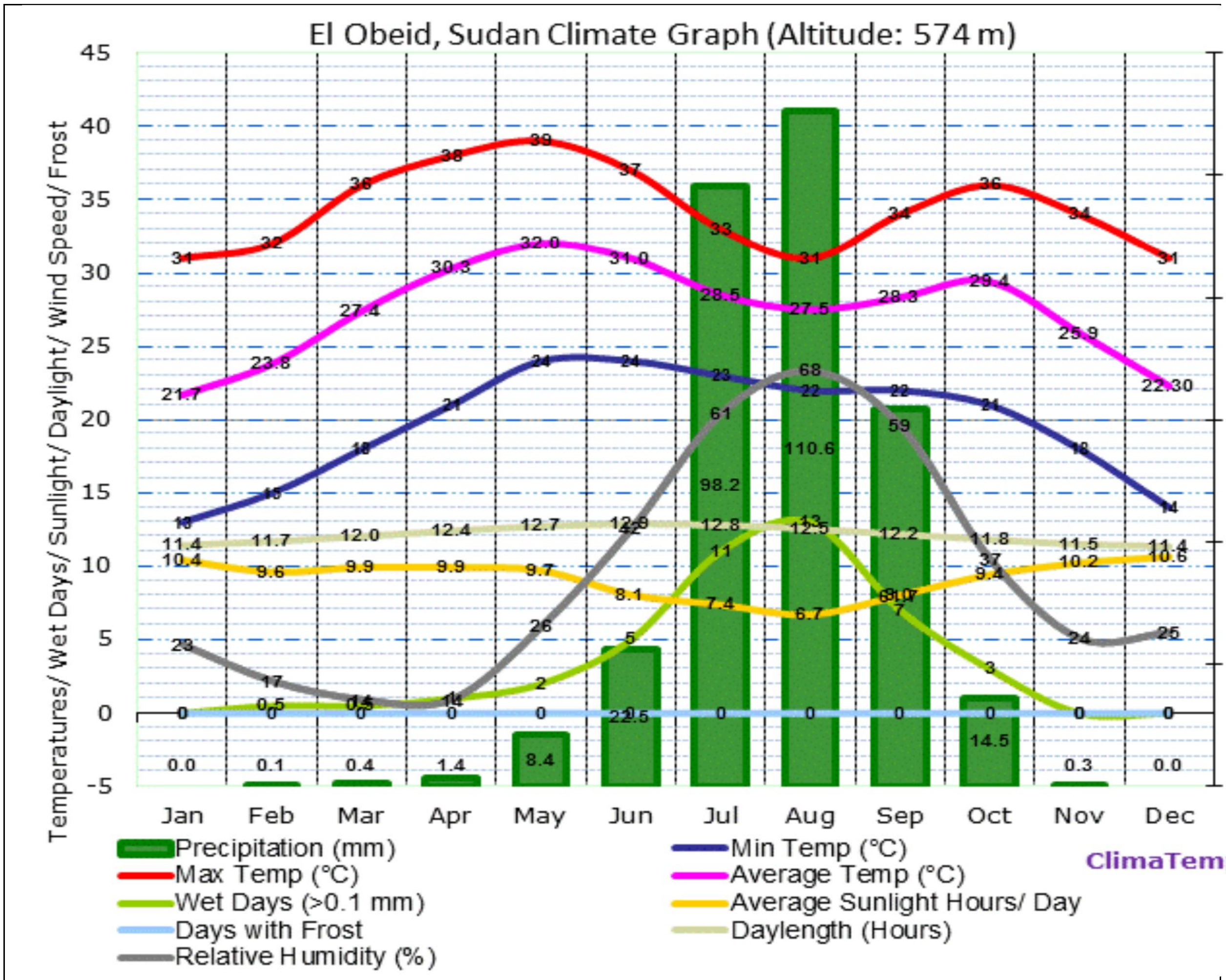
Figure (3.1): Arid Zone – Climate Data of El Fashir.



El Gedaref

Source: Task II – Sudan’s Resources for Enhancing Food Security.

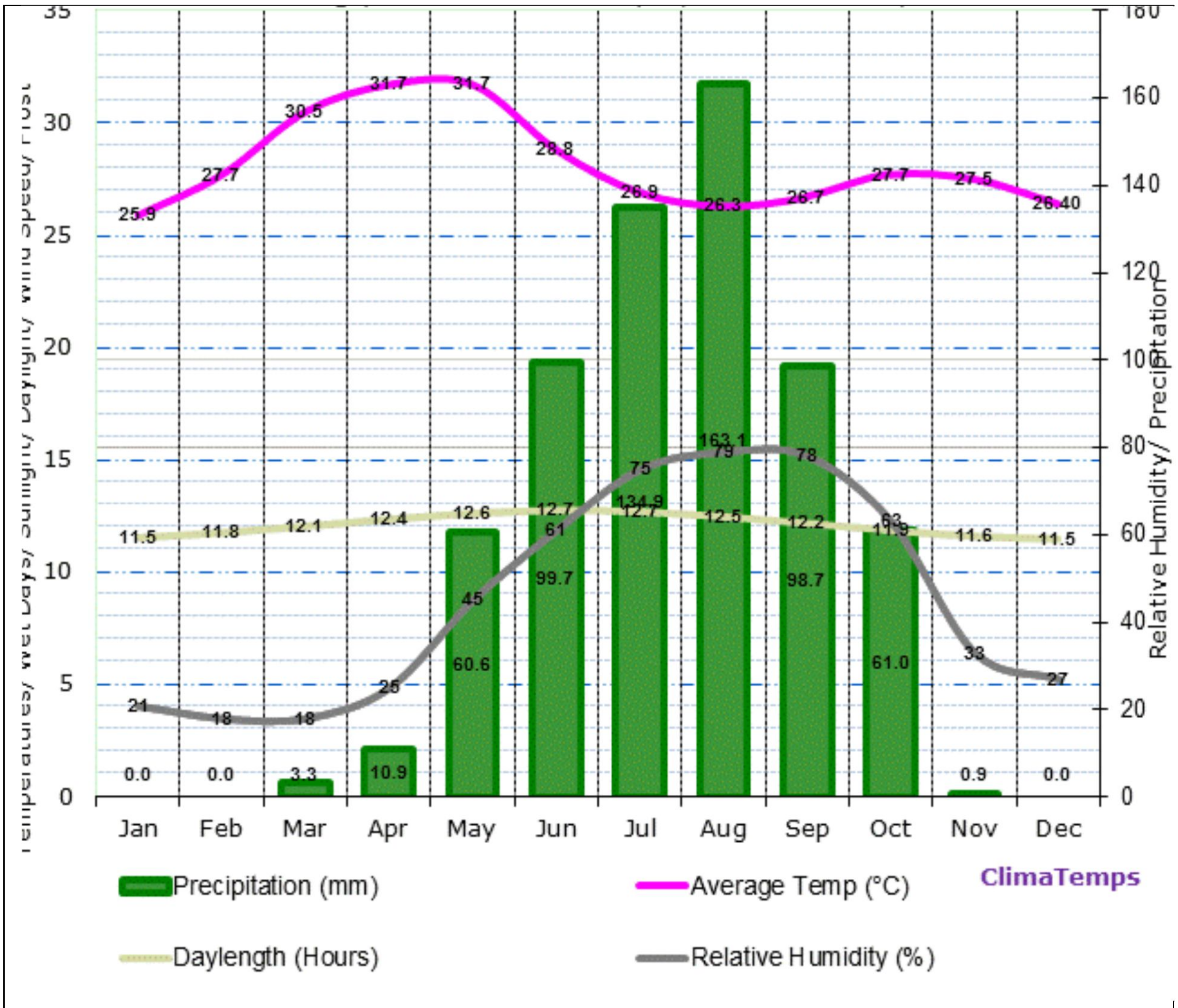
Figure (3.2): Semi Arid Zone – Climate Data of El Gedaref .



El Obeid

Source: Task II – Sudan's Resources for Enhancing Food Security.

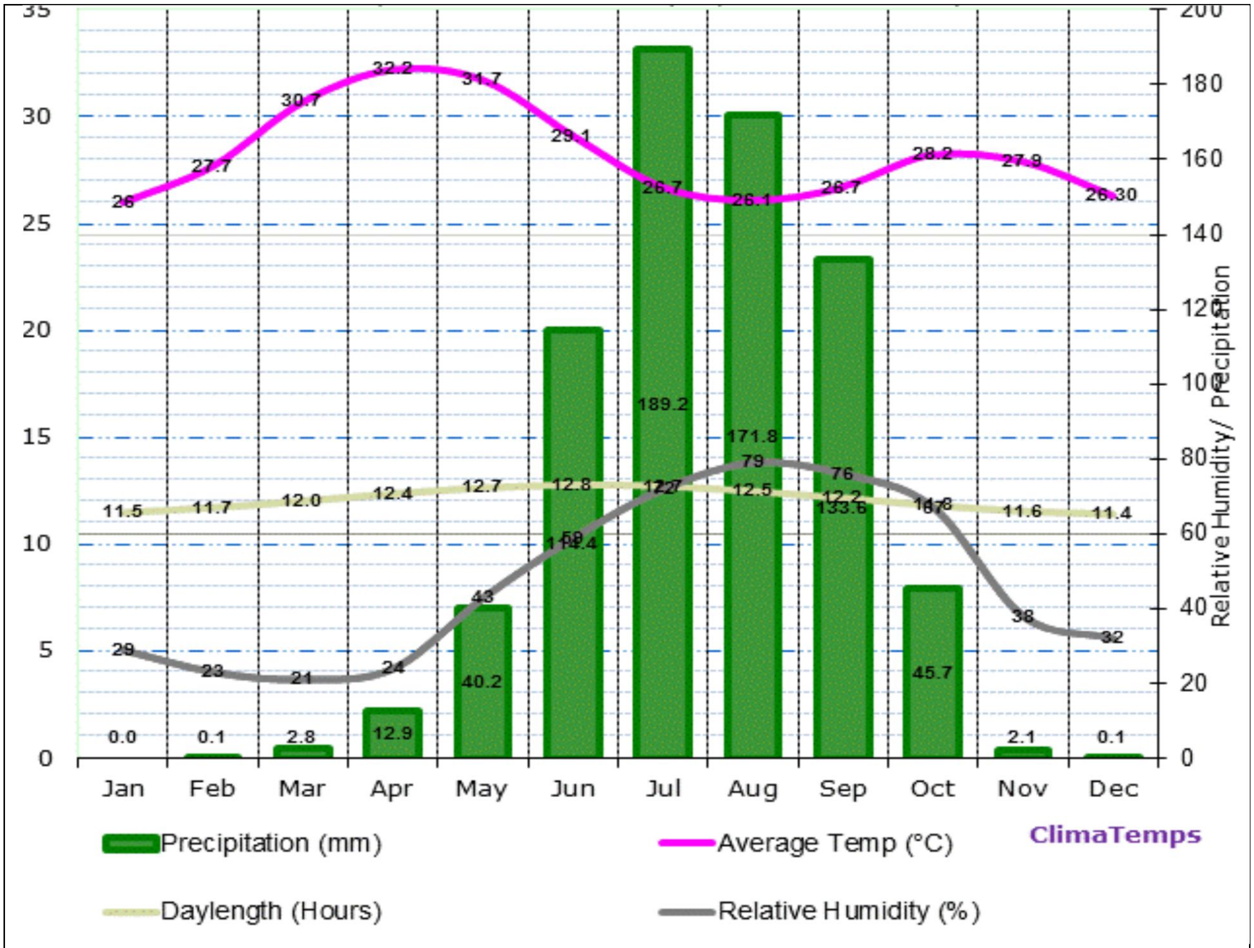
Figure (3.3): Arid Zone – Climate Data of El Obeid.



El Dalang

Source: Task II – Sudan's Resources for Enhancing Food Security.

Figure (3.4): Semi Arid Zone – Climate Data of El Dalang.



El Damazin

Source: Task II – Sudan's Resources for Enhancing Food Security.

Figure (3.5) : Semi-arid Zone - Climate Data of El Damazin.

3.2 Types and sources of Climatic data

The climatic variables used were rainfall, air temperature and reference evapotranspiration (ETo). We used observed data as well as downscaled global climate model data (GCM). Observed data was provided by the Sudan Meteorological Services Department (SMSD).For the study, the daily Satellite data (air temperature, precipitation, wind, and relative humidity) have also been downloaded from*http://globalweather.tamu.edu/#* website in file format for a given location,(South Latitude (12),West Longitude (31), North Latitude (16), East Longitude (34)and time period, (1/1/1979 to 12/31/2014). The numbers of downloaded weather stations were made for each one of the five regions.

3.3 Input Data :-

3.3.1. Model Parameters and Input Data

- **Weather Data:** The weather data required by Aqua Crop are the daily values of minimum and maximum air temperature, ETo,rainfall and solar radiation (Raes et al., 2009, Stedutoet al., 2009). The standard procedure is to calculate daily reference evapotranspiration (ETo) following the FAO Penman Monteith equation (Allen et al., 1998).
- **Soil Data:** The required input soil parameters for Aqua Crop are the saturated hydraulic conductivity (Ksat), volumetric water content at saturation (θsat), field capacity (θFC), and permanent wilting point (θPWP).These parameters were derived from field measurements.
- **Crop Yield Data:** During the 1983 and 2013 seasons, actual field reported yield data was collected from the data bank of Federal Ministry of Agriculture for Sorghum crop in each one of the five regions Aqua Crop requires identifying generic growth stages of time to emergence, maximum canopy cover, start of senescence, and maturity. For the purpose of Aqua Crop simulation, time to emergence, maximum canopy cover, and start of senescence were based on field observations.

3.3.2 Input data requirement of Aqua Crop Model

1. Climate data

i.Daily /10 days/monthly Rainfall; ii. Daily /10 days/monthly ETo ; iii. Daily /10 days/monthly Temperature; iv. CO2 concentration

2. Crop data

i. limited set (crop development and production parameter which include phonology and life cycle

Length)

ii. Full or all crop parameters: a. Crop development at no water, fertility and Salinity stress : b. Evapotranspiration ; c. Crop water productivity ; d. Water stresses ; e. Air temperature stresses ; f. Soil salinity stress ; g. Effect of soil fertility stress ; h. Calendar of growing cycle

3. Management data

i. irrigation type : a. Soil fertility :

ii. Field; b. Mulches ; c. Field surface practices

iii. Surface runoff soil bund occurrence

a. Characteristics of soil horizon (no. of soil horizon, thickness, PWP, FC, SAT, Ksat)

i. Soil profile

b. soil surface (runoff, evaporation)

c. restrictive soil layer

d. capillary rise

4. Soil data

ii. Ground water (constant or varying depth and water quality)

5. Simulation data

1. Simulation period (linked to growing season)
2. Initial condition

Initial soil water content soil layer thickness soil salinity (Specified for specific layer)

All these input data were used in the model to predict the yield, water productivity, and biomass and harvest index of a given crop. However, the model should be calibrated and validated using the data acquired from field experiments for its further use.

3.4 AQUACROP Yield Prediction Model

Aqua Crop (Raes et al., 2009) is a crop water productivity model developed by the Land and Water Division of the Food and Agricultural Organization (FAO). It simulates yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production (FAO, 2009). The model does not take into consideration such factors like pests, diseases and weeds. Aqua Crop requires the following input data: daily weather data (air temperature, reference evapotranspiration and rainfall), soil texture data (sand, clay, loam, in %) and crop parameters (initial, final and rate of change in %; canopy cover; initial, final and rate of deepening in root depth; biomass water productivity; harvest index; typical management conditions such as irrigation dates and amounts, sowing and harvest dates, mulching, etc). If daily climatic data is not available, 10- day and monthly data can be used as input. Details of the crop model that include: penology, growth and water balance are contained in FAO (2009).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Benchmarking Yield Gaps

Specific data requirements representing: climate (long-term data set), soil profile characteristics, Sorghum crop and current practices related to water management, cultural practices, fertilization, level of crop protection and other agronomic practices relevant to actual yields were collected from five cities representing various regions of Sudan. The stations include:

- Western: North Darfur – El Fashir-(rain fall 100 to 200 mm).
  North Kordofan: El Obayied: -(rain fall 200 to 300 mm).
- Central Region (Gezira, Sennar, White Nile, and Blue Nile): -(rain fall 300 to 400 mm) The central region is considered the most important cereal producer in the country. The region’s contribution to total grain production is estimated at over 30 percent owing to the presence of the major irrigation scheme (Gezira), part of Rahad scheme, rain fed production and minor irrigation schemes in each state.
- Eastern :Gadaref: -(rain fall 400 to 600 mm) .
- Southern : South Kordofan: -(rain fall 600 to 700 mm) .

Characteristics of each station are detailed in Chapter three. Actual yield is that reported by Federal Ministry of Agriculture, Potential yield is determined by *Aqua Crop model and* attainable yield is the long term average reported by Fao.org food security mission (FAO-SIFSIA-N,FAO-ERCU SUDAN, Ministry of Agriculture and Irrigation, Food Security Technical Secretariat (FSTS), Strategic Reserve Corporation -Quasi crop and food supply assessment mission–

January 2012). The data is collected for 30 years for the comparison of the long-term productivity using the cumulative distribution functions to show the relative risk levels. Probability analysis was conducted to estimate the most reliable yield.

From the actual yield information and the simulated yield, the capacity of rain fed environments and the yield gap (simulated minus actual yield) was determined and given in figure (4.1) (shows the average values of Actual, Potential yield, and yield gap for each one of the studied stations for the last 30 years.

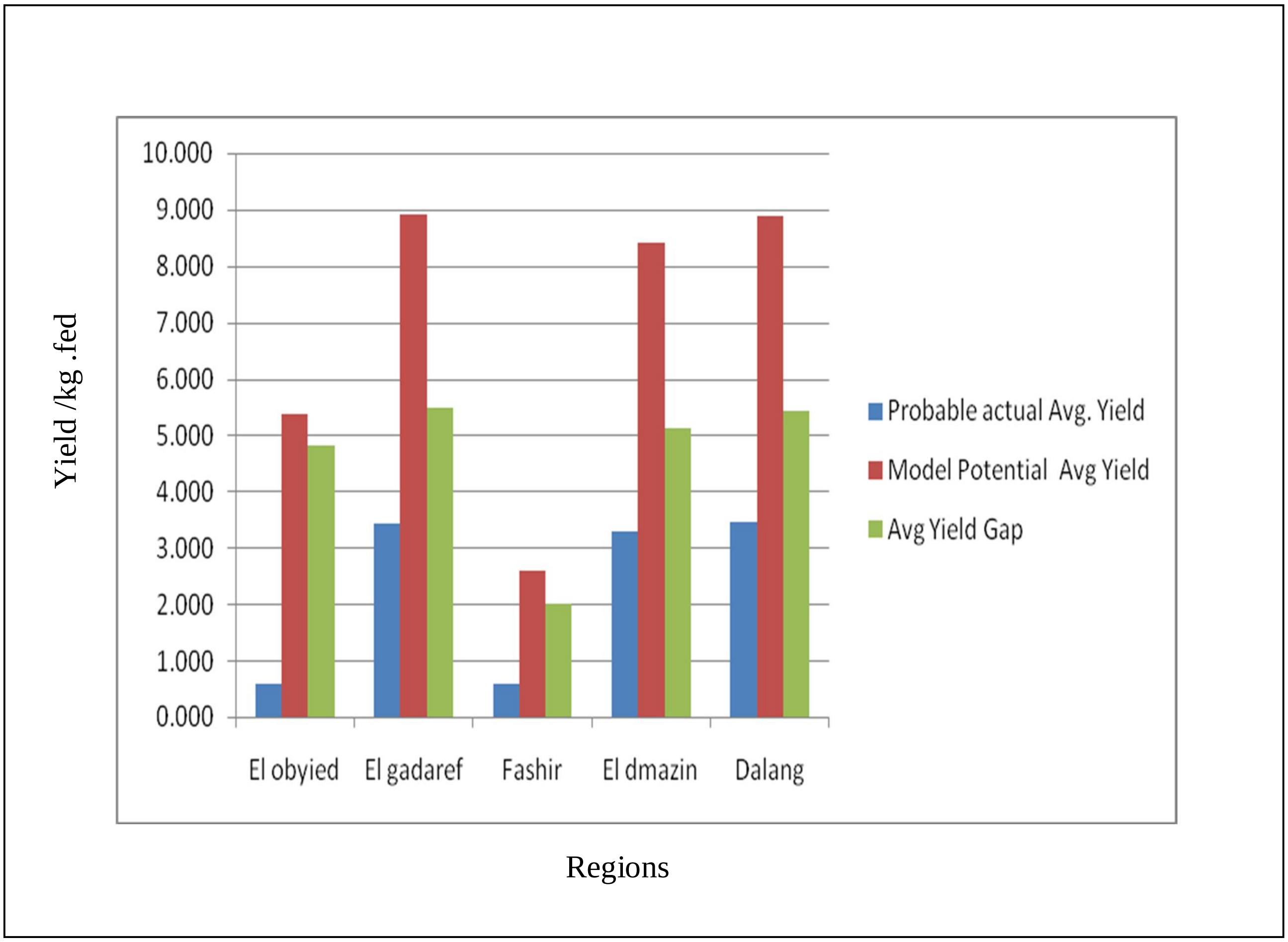


Figure (4.1) Actual, Potential Grain yield and yield gap (Kg/ fed) for the studied five regions.

It is evident from the figure (4.1) that: in all regions that there is wide gap between potential yield and actual one. However, the actually attained yield is less in the stations with low rain fall. This calls for introducing rain water harvesting techniques to avail water and thereby increase the crop yield. However, even in the station with high rain fall (e.g. Dalange and Gadaref) attained yield is far less than the potential. These indicate that water is not only the limiting factors and other crop cultural practices need to be improved.

Results from different years were employed to give some clues as to the possible reasons for the yield gap in traditional and semi-mechanized rain fed Sorghum production systems (i.e. low soil fertility, pest, disease, and weed limitations, socio-economic constraints, or low-yielding crop varieties, etc.). A specific application of this approach for assessing Sorghum yield constraints in a region were investigated as detailed bellow. The objective is to help in identifying the possible underlying causes of the yield gap and identify regions and crops where substantial improvements in production and productivity may be possible.

In an average year, most of the country's sorghum is produced in the semi-mechanized rain-fed sector, followed by the traditional and irrigated sectors. Rain-fed yields (semi-mechanized and traditional sectors) are generally of the order of 0.5 t/ha, while those in the irrigated sector are usually about 2 t/ha

Table(4.1):show the five regions for potential-Actual and yield gap.

	ClimateZone				
Zone	El dmazin	El gadaref	El obyed	El Facher	El Dalang
Potential	3536.3	3740.9	2261.2	1086.2	3736.7
Actual	300.4	226.7	119.3	136.8	242.4
Yield gap	3235.9	3514.2	2141.9	949.4	3494.3
Yield gap%	91.5	93.9	94.7	87.4	93.5

The semi-mechanized rain-fed sector is Sudan’s largest producer of sorghum, and about half of this comes from Gedaref state; other significant producers include Sennar, Kassala, BlueNile, White Nile and South Kordofan states. Traditional sorghum production is important in most states apart from Northern. At about 0.5 t/ha, yields are low in both the semi-mechanized and traditional rain-fed sectors.

A- Semi-mechanized Rain-fed Sorghum, Gedaref State.

B- Irrigated Sorghum, Gezira Scheme.

C- Sorghum Crop, Traditional Rain-fed, Kassala State.

D- Failed Sorghum Crop, Traditional Rain-fed, West Darfur .

Figure (4.2): Status of Sorghum Crop in Different Producing Areas in Sudan.

It is interesting to compare Sudan's recent average national sorghum yield of 0.6 t/ha (irrigated and rain-fed) with those of neighboring and other countries (Egypt5.2t/ha; Eritrea 0.3t/ha; Ethiopia 2.1t/ha; India 0.9 t/ha. The area of harvested sorghum can fluctuate dramatically from year to year (Table 4.2). This fluctuation may be partly explained by varying rates of production from planted area to harvested area, but other major causes include rainfall variation and market expectations. Farmers tend to grow more sorghum following a year of high sorghum prices; a market glut then depresses prices and farmers decide to grow less the next year. In the semi-mechanized rain-fed sector there is a tendency for these fluctuations to run counter to those of sesame; after a year of low sorghum prices the area under sesame may increase; if this then brings down the price of sesame, farmers are encouraged to return to sorghum the following year.

The main pest problems in sorghum production in Sudan are birds(Queleaquelea), which weed (Strigahermonthica), sorghum bug (Agonoscelispubescens) and sorghum midge (Contariniasorghicola).

In the last 7 years from 2005/6 to 2012/13 sorghum was the most widely grown crop with a planted area of around 8 million hectares (Table 4.2). Of this area only 6% was irrigated and the remaining 94% was rain-fed. In the rain-fed area the semi-mechanized sector is most important with 63% of the area. The distribution of growth of rain-fed sorghum is shown in Table 4.2 The semi-mechanized sector is mainly concentrated in the Eastern and Central Regions, in particular Gedaref State, where almost half the semi-mechanized sorghum is grown and where traditional rain-fed sorghum is completely absent.

Table (4.2): Sorghum Planted and Harvested Areas ('000 ha), Production ('000 MT) and Yield (kg/ha) – Average 7 years 2005/6 to 2012/14

Yield	Production	Harvested	Planted	State
				Mechanized Rain-fed
371	195	484	835	Sennar
422	136	331	428	White Nile
645	151	245	325	Blue Nile
382	559	1,381	2,191	Gedaref
406	116	296	539	Kassala
413	5	12	17	North Kordofan
502	160	318	436	South Kordofan
449	1,322	3,067	4,771	Total Mechanized Rain-fed
				Traditional Rain-fed
586	27	43	58	River Nile
293	9	27	42	Khartoum
347	100	273	406	Gezira
439	60	128	193	Sennar
529	86	160	216	White Nile
670	32	50	66	Blue Nile
324	20	60	117	Kassala
473	5	10	14	Red sea
254	90	340	477	North Kordofan
590	220	354	426	South Kordofan
204	15	67	123	North Darfur
760	82	95	148	West Darfur
92	5	21	33	Central Darfur
31	4	18	30	East Darfur
544	176	327	512	South Darfur
467	931	1973	2861	Total Traditional Rain fed
447	2253	5040	7632	Total Rain-fed

Source: Federal Ministry of Agriculture-department of statistic.

Traditional rain-fed sorghum is grown over a larger area, including Darfur, where mechanized farming is absent. Average yields from the traditional sector (419 kg/ha) are lower than from the mechanized sector (467 kg/ha). These low yields reflect both the unreliable rainfall and the absence of inputs such as fertilizer and weeding. The proportions of the planted areas actually harvested are 64% for the mechanized sector and 69% for the traditional sector.

4.1.1 Semi-mechanized Rain-fed Farming :-

Since the 1970s there has been a rapid expansion in Sudan of the area under semi-mechanized rain-fed farming (SMRF) from around 2 million feddans (840,000 ha) to around 13.75 million feddans (5.8 million ha) now. The expansion of the area is continuing. The area is characterized by large areas of vertisols, with rainfall varying from a low of around 400 mm in the north to 800 mm in the south. There are also substantial rangeland resources and livestock in the same area. The farm sizes range from small holders with less than 40 feddans up to massive farms with over 250,000 feddans. Even the smallest farms generally use tractors for cultivation and some sort of mechanical threshing and so are classified as semi-mechanized. Productivity is generally very low, with average yields of about 419 kg/ha for sorghum and 259 kg/ha for sesame (see Table 4.3).

Yields have declined over time and are still declining. A similar situation is found in the livestock sector, which is often using the same land.FAO(2009) report concluded that all semi- mechanized farmers make very low cash returns and most operate at a loss. The study team estimated that small holders made a small profit of SDG 18 per feddan (which would be a loss if the cost of family labour was included) and large farms made a loss of SDG 74 per feddan.

The FAO(2009) report concluded that most impacts of SMRF have been negative. These have included the loss of traditional lands and traditional grazing lands and livestock movement routes, degradation of water supplies and competition with livestock owners, resulting in conflicts, and loss of life and destruction of property. Large areas of forest and rangeland have been effectively destroyed and soils degraded. It was concluded that the SMRF sector is in dire straits. Yields from rain-fed agriculture vary widely from year to year, the main influence being the quantity and distribution of rainfall. In general, in years with high rainfall yields should be higher, but it is also possible that untimely rainfall can delay planting and cause excessive weed growth, both of which will cause a lowering of potential yields. There are a number of sources for yields. The World Bank study on mechanized farming which covered the whole country reported the following yields (Table 4.3).

Table (4.3) Yields of Rain-fed Sorghum in Sudan:

Year	96-97/2000-1		2005-2006		2006-2007		2007-8		All	
	Yield*kg/fed	Harvested %	Yield*kg/fed	Harvested %	Yield*kg/fed	Harvested %	Yield*kg/fed	Harvested %	Yield*kg/fed	Harvested %
Sorghum										
SMFR	170.4	80.50%	158.6	75.90%	162.6	70.20%	115.4	76%	161.1	78.10%
Small holders	191	84.40%	181.9	75%	253.7	79.90%	202.2	86.40%	199.4	82.90%
Mean	180.7	82.45%	170.25	75.45%	208.15	75.05%	158.8	81%	180.25	80.50%
Potential	3840.3	82.45%	3319.3	75.45%	3109.2	75.05%	3697.5	81%	3773.1	80.50%
Gap in SMFR	3669.9	83.10%	3160.7	75.30%	2946.6	76.67%	3582.1	83%	3612	81.30%
Gap in small holders	3649.3	82.67%	3137.4	75.40%	2855.5	75.59%	3495.3	82%	3573.7	80.77%

The study reported that areas are not harvested because of a combination of the following factors:

- Late sown crops which fail to reach maturity .
- Shortage of rain at the end of the season Damage by birds, locusts, rats and insects .
- Low prices and uncertain market conditions
- Yields too low to justify the cost of harvesting; in this case sorghum is sown to pastoralists for grazing on most farms the yield is put in sacks and stored in the yard, then transported to markets or stores in villages, towns or cities.

4.1.2 Present Agricultural Practices

The majority of farms do not follow any sort of rotation. The initial cultivation and seeding is usually done simultaneously using a wide level disc harrow with a seeder box, which broadcasts the seed (not planted in rows). The tractor employed for this work is of 70-90 HP. Most farmers do no preparatory cultivations before planting although some may do one or two. Planting is carried out between June and September. Planting may be delayed because of late finance or lack of machinery. Only a minority of farmers uses any fertilizer and the use of pesticides for insect or weed control is rare. Weeding, if it is done, is usually by hand. Most crops are harvested by hand with the exception of sunflowers which are usually combining harvested. Sorghum is normally collected in piles by hand and threshed manually or using a stationary thresher or a stationary combine harvester.

On AAAID farms (e.g. Agaadi) and some other farms a more high technology rain-fed farming is employed, where herbicides are used for both weed and moisture control, planting is in rows and mechanical harvesting, even of cotton, is employed. These are the exception. On the majority of rain-fed farms the technology is low and so are the yields.

4.1.3 Cause of Poor Performance of Semi-Mechanized Rain-fed Farming

Government policy over the years has supported increases of the area under cultivation rather than encouraging measures which would increase yields. A lot of this increase in area has been in un-demarcated areas. The land tenure system is confused with leases granted by a number of different organizations. Leases are of various durations and with differing conditions. Most leases are for 10 years or less. Traditional land use and rights of livestock owners are often not respected and a cause of conflict.

Farmers have low levels of investment, the level of technology is low, and there is a lack of investment in farm infrastructure such as housing, storage facilities and water supplies. At the same time there are poor rural roads with a lack of all-weather access to most areas and the railways have collapsed in most rain-fed areas. There is little rural electrification and farmers have to rely on generators. Many areas – although the networks are extending - are too remote for mobile phones to work.

Farmers have a difficulty getting finance from the Agricultural Bank of Sudan. When this is provided it is often too late resulting in delayed planting after the rains have arrived and weed infestations are high.

There is little support to the sector from the research and extension services, who concentrate their sometimes limited resources on the irrigated farming sector.

Marketing is another obstacle faced by the farmers. This is poorly organized, and exports are constrained because of a number of factors.

Finally the taxation is an impediment. Zakat is charged at a rate 10% on revenue instead of net returns or profit. Even if farmers do not make a profit they still have to pay this tax.

4.1.4 Possibility of Expanding Rain-fed Area

Expansion of the area of rain-fed production of those crops that could contribute to the food security of Arab countries may be possible in those parts of the country receiving an average annual rainfall of at least 500 mm. For instance, maize yields of 2.4 t/ha has been achieved under rain-fed conditions in Sennar (with average 445 mm rainfall). In areas of lower average annual rainfall, sorghum and millet yields are unreliable, although high yields may be achieved once in about every five years. In North Kordofan, where mean annual rainfall is about 200 mm, an average of about 30,000 t of watermelon seed are produced from about 500,000 ha. However, the unreliability of rainfall in such areas is illustrated by the fact that in the four years 2010 - 2013 watermelon seed production in North Kordofan fluctuated between 26,000 and 120,000 t. Each year, a significant proportion of the land that is within the 500 mm-plus average annual rainfall bracket is unused for one or more of several reasons, chief among which are lack of investment, civil unrest, and uncertainty on the part of farmers as to which crop or cropping pattern is likely to give a positive return to their investment.

Civil unrest is a major factor in the under-utilization of land in South Kordofan, in Darfur, and to a lesser extent in Blue Nile. Lack of investment, due not only to civil unrest but also to difficult access and poor infrastructure, plays a part in Blue Nile, as is evident from the relatively small proportion of land that is productive on the Agaadi project. Much of the under-utilization of rain-fed land in Gedaref state may be attributed to farmers’ uncertainty as to the return on their investment. The Mechanized Farming Corporation (MFC) is currently addressing this problem by preparing cropping recommendations for all the various zones of the demarcated land based on climate and soil data as well as on past yield data. This undertaking will take a number of years to complete, but it should increase not only the area of cultivation but also the crop yields achieved.

4.2 Seasonal Variability grain and Biomass Production for different climate regions

Figure (4.6) shows the inter-annual variability, of grain and biomass yield in the five regions (Kg/fedan). The figures shows that the variability of both grain and biomass yield follows the same trend. It is also evident that much inter-annual variability is in El Fashir and El Obayied regions. These regions are characterized with late and low rain fall amount. In contrast less inter-annual variability is found in the other regions with higher rain fall amount.

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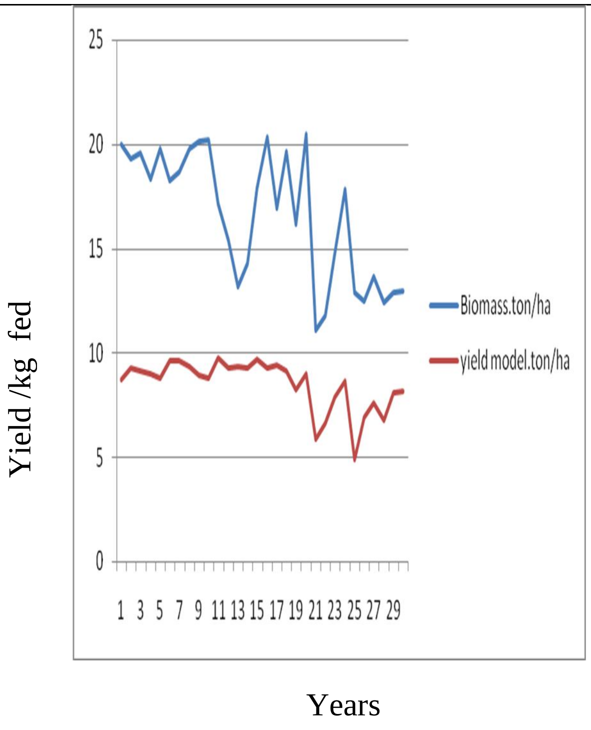

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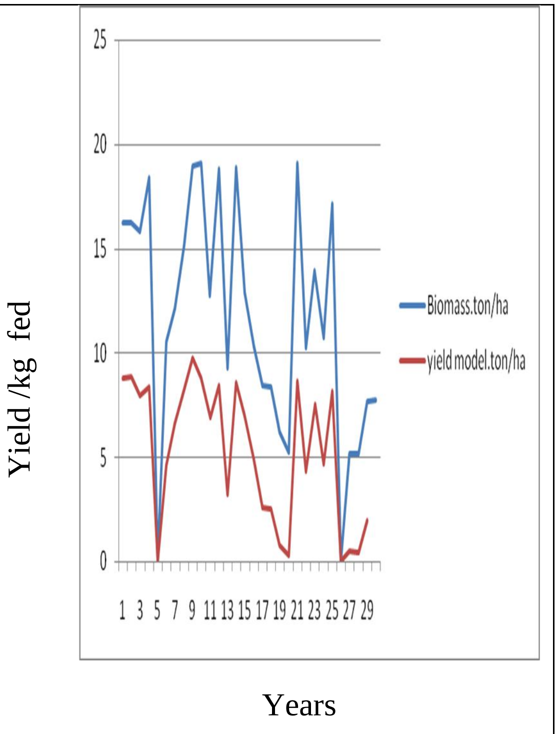

</td>
</tr>
<tr>
<td>El Damazine</td>
<td>El Obayied</td>
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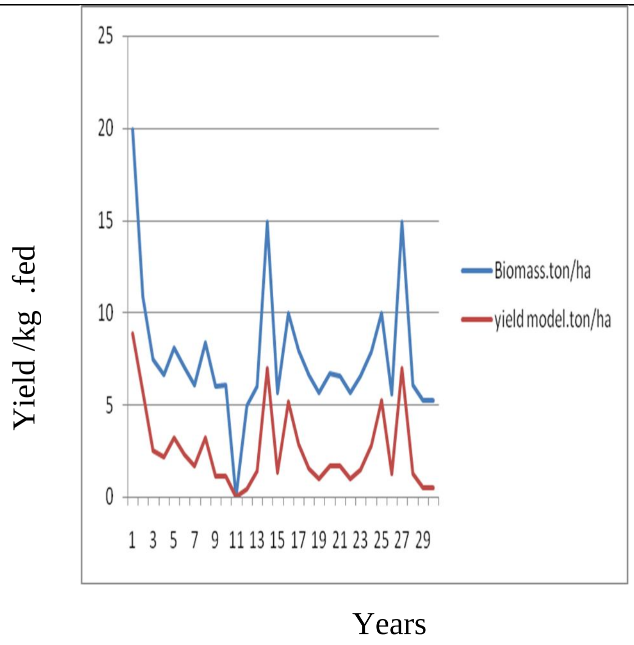
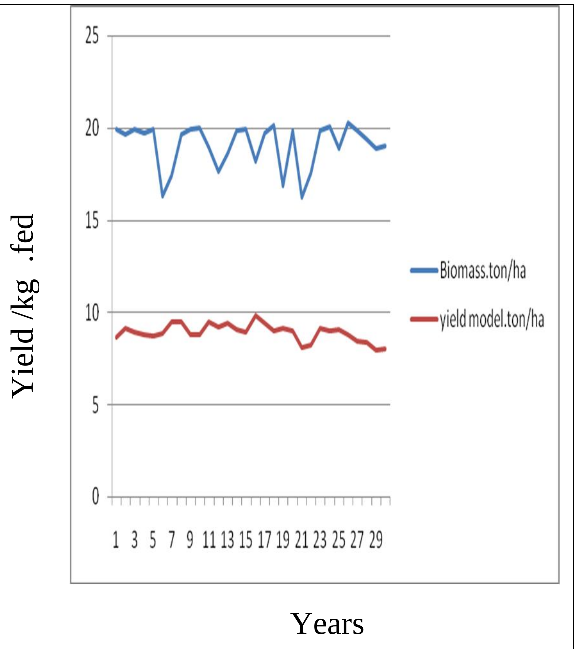
</table>

a- inter-annual variability, of grain and biomass yield in El Damazine and El Obayied(kg/fed).

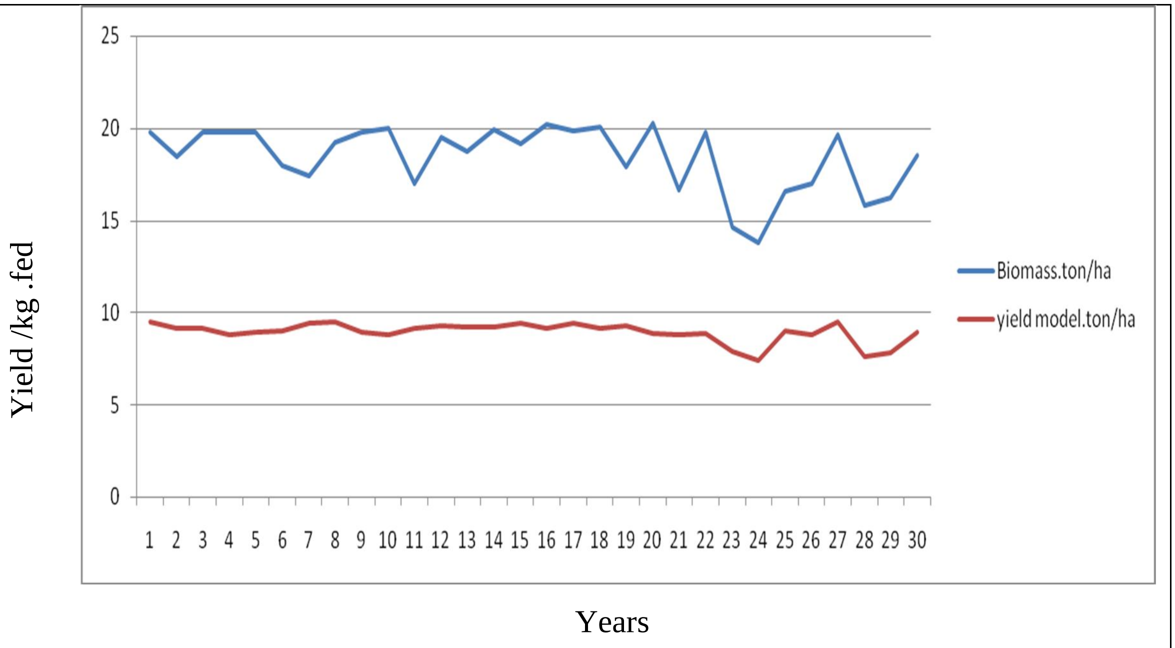


El Fashir



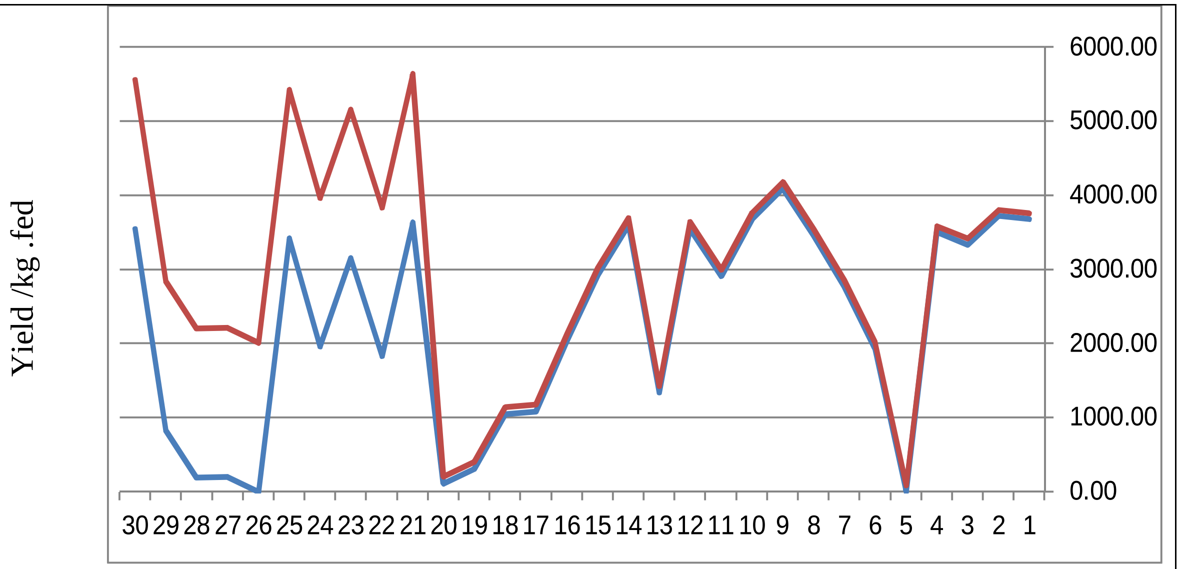
El Dalang

b-inter-annual variability, of grain and biomass yield in El Fashir and El Dalang(kg/fed).



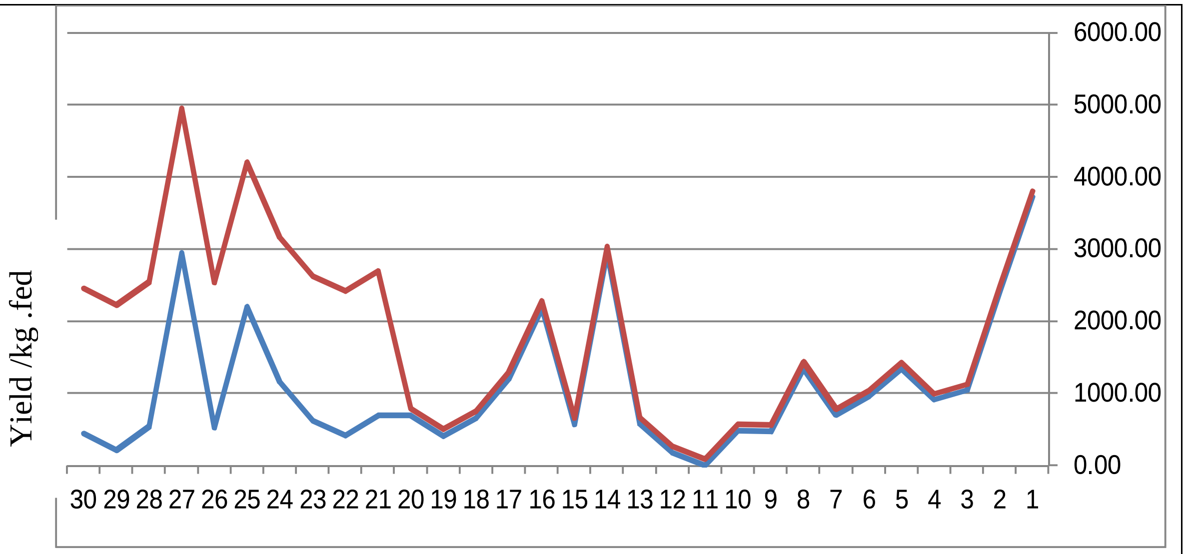
El Gadaref

c-inter-annual variability, of grain and biomass yield in El Gadaref(kg/fed).



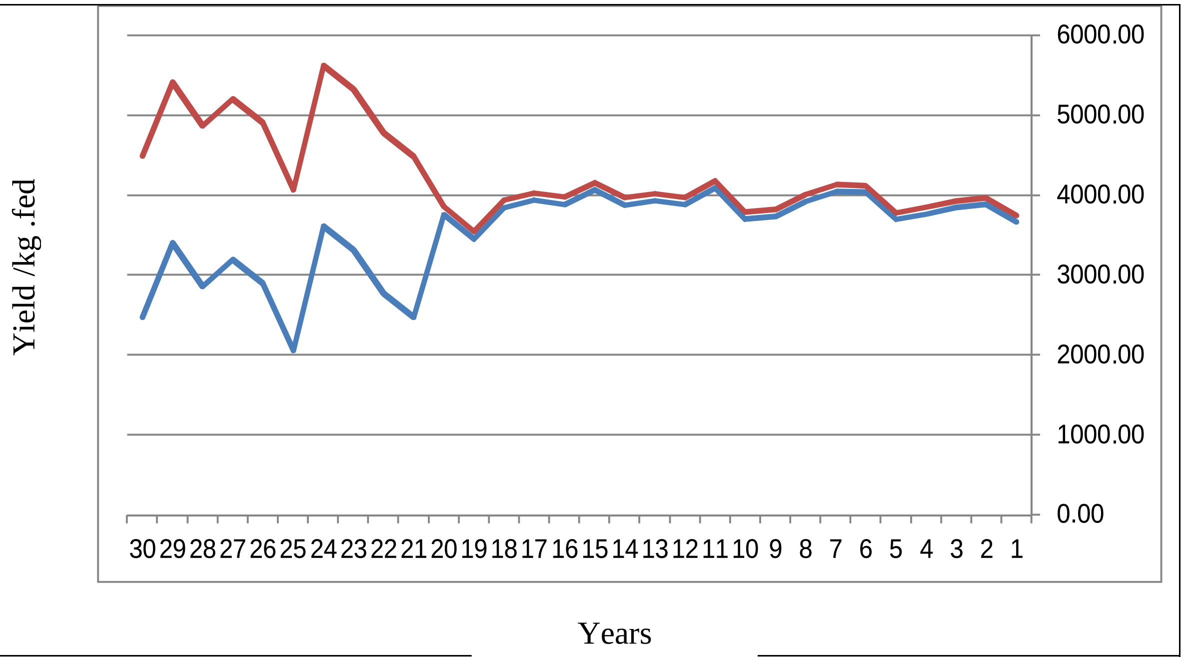
El Obayied

a-Inter-annual variability, grain yield in El Obayied(kg/fed).



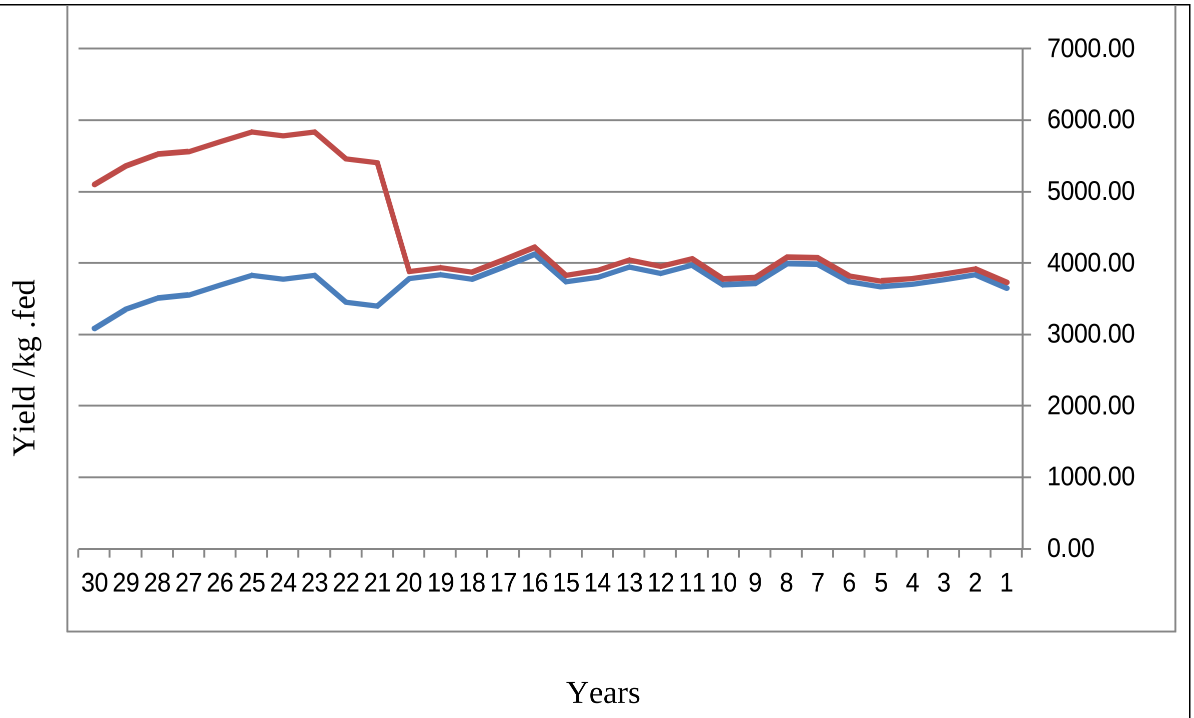
El Fashir

Years



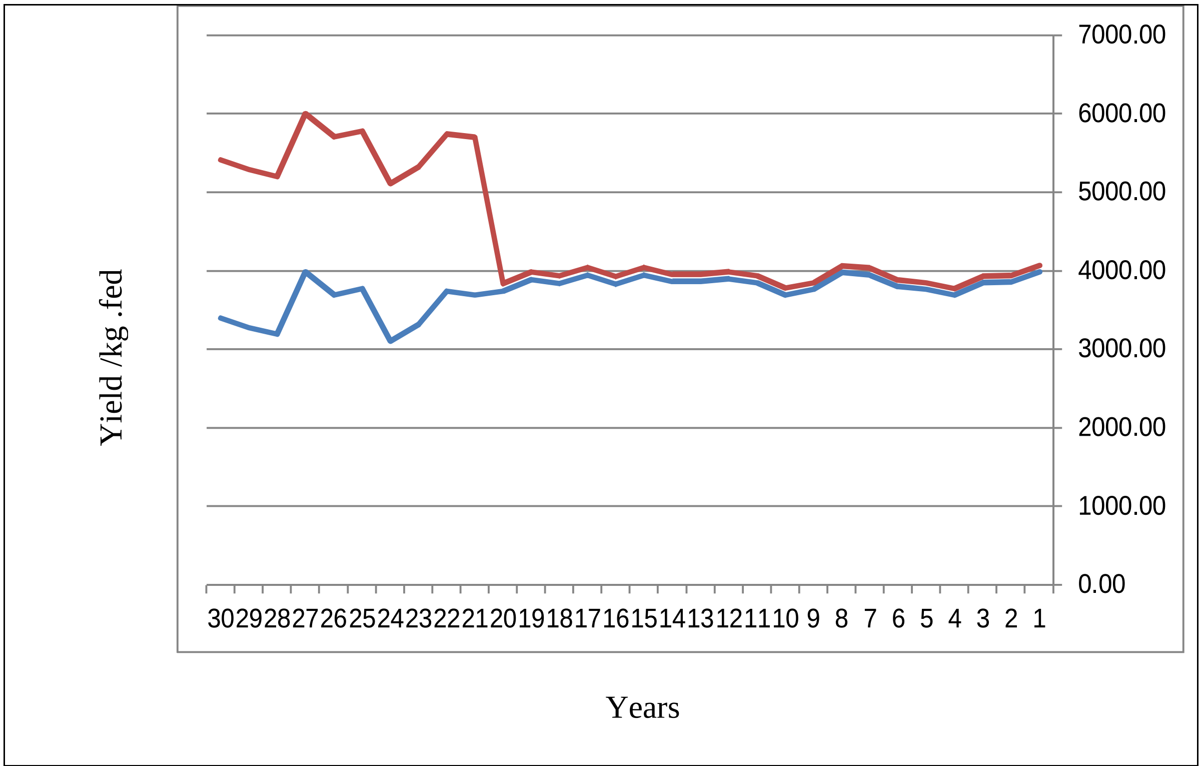
El Damazine

c-Inter-annual variability, grain yield in El Damazine (kg/fed).



El Dalang

d-Inter-annual variability, grain yield in El Dalang(kg/fed).



El Gadaref

e-Inter-annual variability, grain yield in El Gadaref (kg/fed).

4.3 Determining the optimal planting date :-

Adjustment of sowing dates for sorghum as one of the adaptations in future climate change scenarios was tested in the modeling framework through shifting by either bringing forward or delaying sowing within a regular interval (Do-15, Do+15 days) with respect to the baseline case, Do being the normal sowing date . Results from the adjustments are shown in Figure (4.7) and indicate increase in sorghum yields under historical climate when early sowing is considered in almost all stations. Decrease in yield with late sowing may be due to incidence of low early rains (rains coming late). In stations with high rains (Dalang, Damazin and Gadaref) it is preferred to sow early to benefit from the probable early rains.

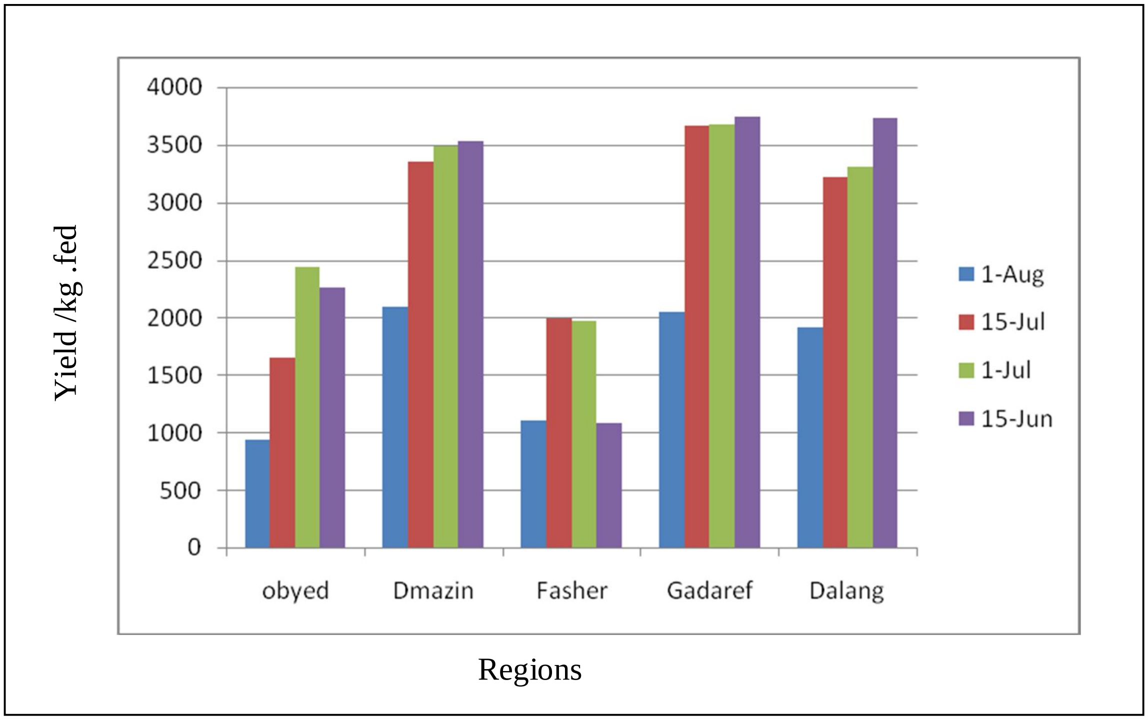
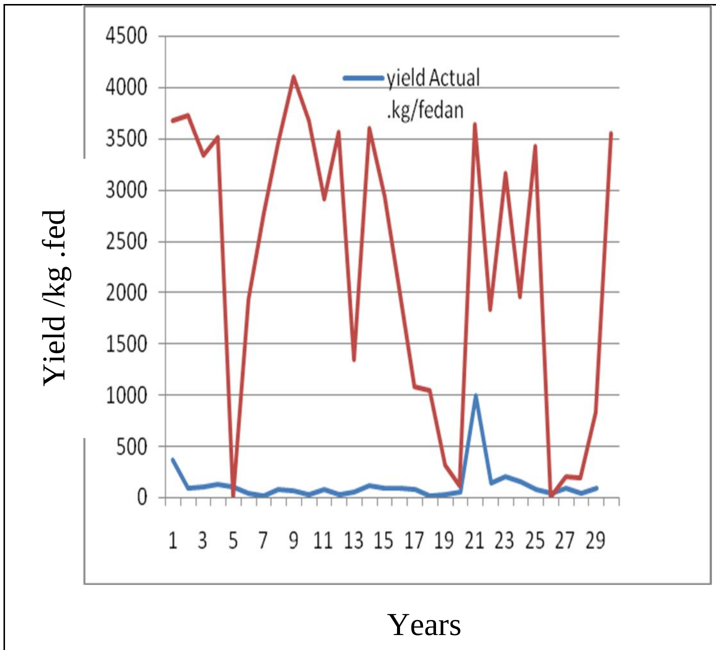


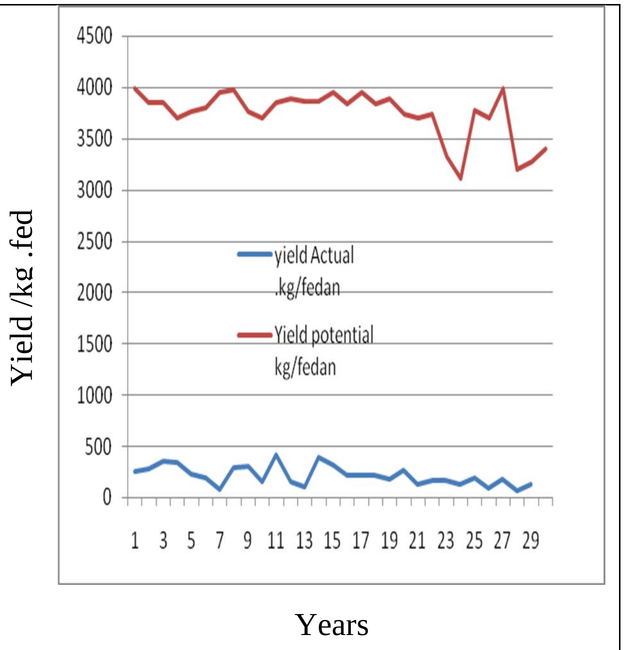
Figure (4.5): Sorghum Grain yield due to changes in sowing dates in the different regions.

Figure (4.5) indicate that there is however a trend towards higher inter-annual variability, i.e. more years with high or low yields. Stations with high rain fall (Damazin, Gadaref and Dalang) show little variations in inter-annual yields but with a tendency towards high yields. Contrastingly, El Obayied and El Fashir show wide variations in yields and a trend towards lower yields. These results seem to suggest that depending on the onset of rain fall, adapting sowing dates may be effective in counteracting adverse climatic effects as shown by the slight increases in median yields compared to yields from baseline. Similar results were reported by Abdel Rahim et al. (2002) for both Sorghum crop and Millet crops. However the erratic nature of rainfall, characteristic of semi-arid areas (which unfortunately cannot be captured by the model) tend to shorten the planting window, such that a delay of two weeks in sowing may cause significant reduction in yields due to shortening of the length of growing period (yield decrease by 43% when sowing date is delayed from 15July (the recommended date by ARC) to 1st of August.This may be due to effects of initial soil water stored from onset of early summer rainfall can influence early establishment of the crop and can contribute to water use and yield later in the season, in particularly in low rainfall seasons.

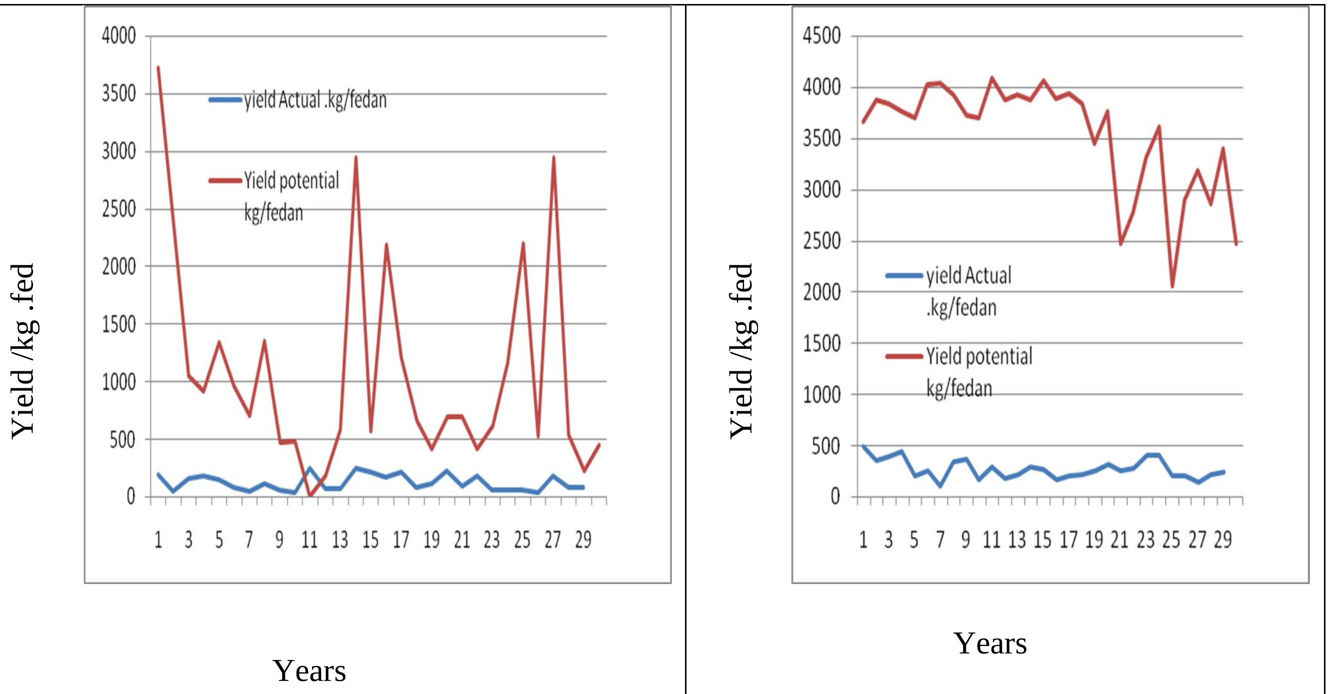
Table (4.4): shows the average Potential model yield for the different sowing dates for each one of the five stations (kg/fed). It is evident from the table that the date with maximum yield for El Obyied, El Dmazin, El Fasher, El Gadaref, and El Dalang are 1-July, 15 – June, 15-July, 15-June, and 15-June respectively.



A- El Obayied

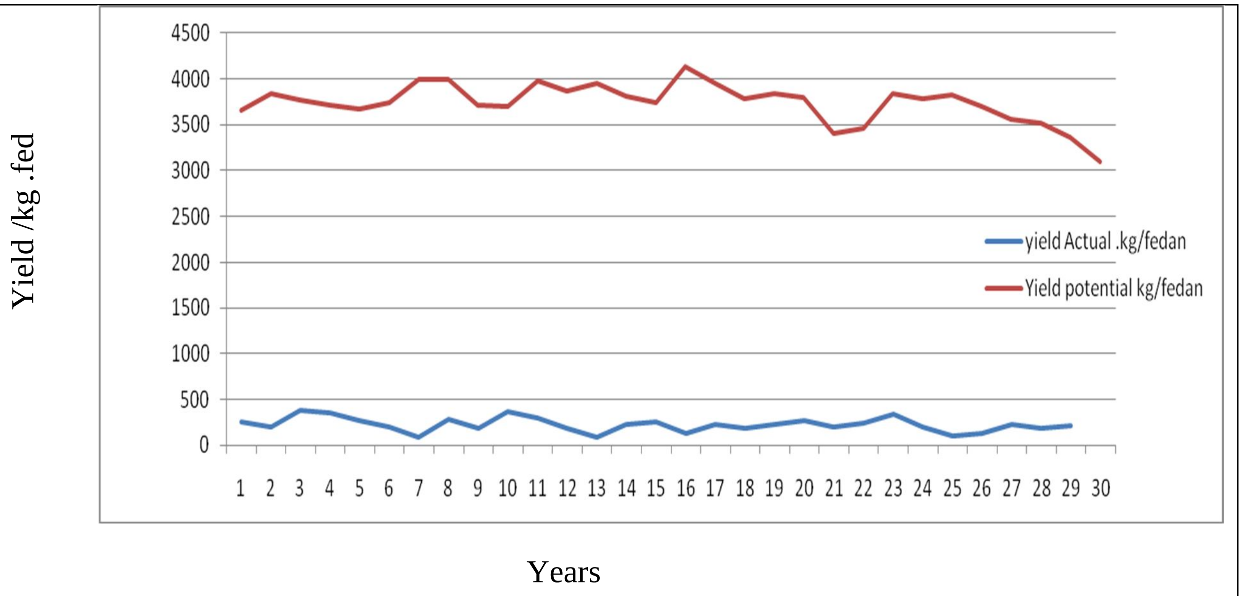


B-El Gadaref



C-El Fashir

D-El Damazin



E- El Dalang

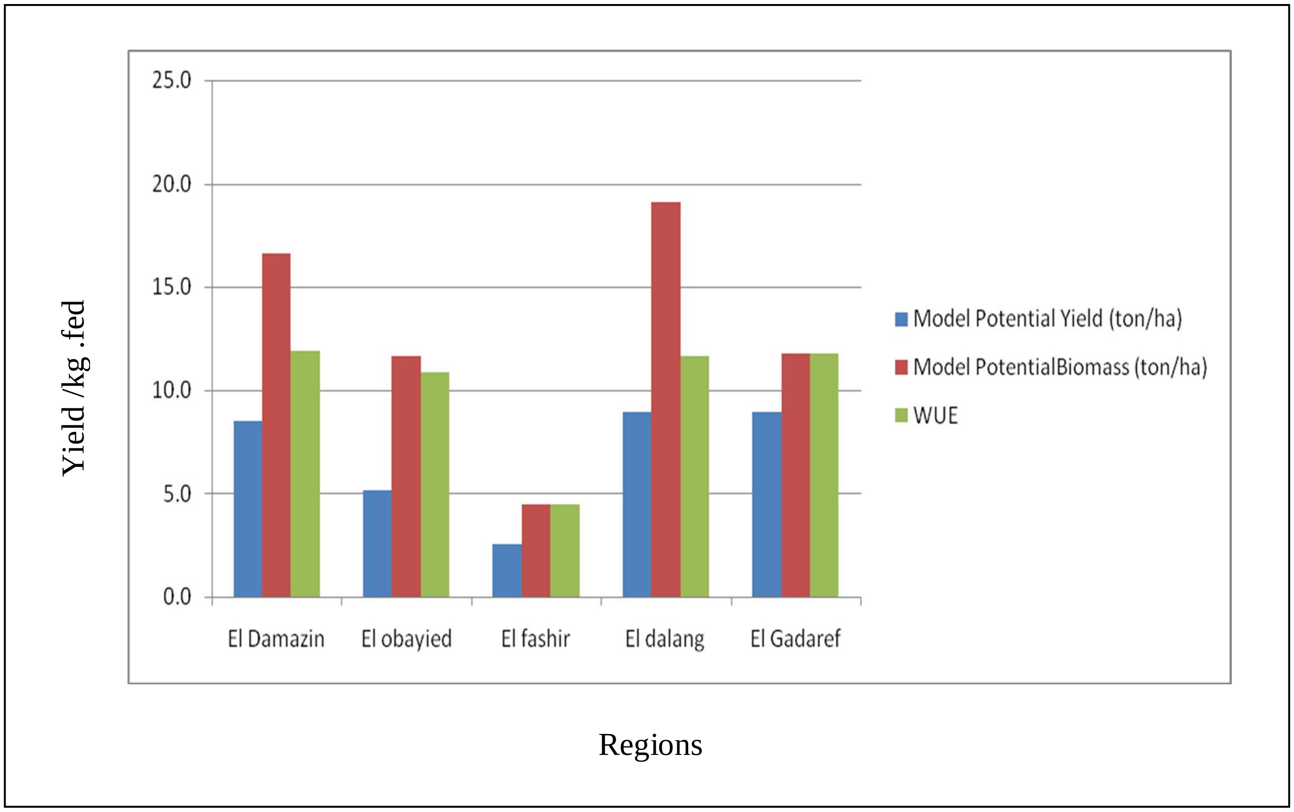
Figure(4.6): Inter-annual variability, of crop yield in each regions (Kg/fed).

Table (4.4): Average Potential model yield for the different sowing dates for each one of the five regions (kg/fed) .

1-Aug	15-Jul	1-Jul	15-Jun	Station
938	1652	2435	2266	El Obyied
2092	3350	3485	3536	El Dmazin
1100	1992	1969	1086	El Fasher
2051	3667	3677	3741	El Gadaref
1917	3222	3311	3737	El Dalang

4.4 Determination of Rain fall water Use Efficiency (WUE)

Figure (4.9) shows the variability of Water use efficiency (WUE) for different climatic regions. The figure indicates that: the obtained WUE is lower in the driest regions of El Fashir, El obyied while it is medium and equal for El Gadaref, and El Dalang and higher for Damazin. This may be attributed to availability of water at crop critical growth stages; where the crop is sensitive to presence of high rain water at the early initial stage and sensitive to water shortage at flowering stage.



Figure(4.7): Variability of Water use efficiency for different climatic regions

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CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary :-

Under the increase of the concern for food security in the world, mainly caused by water resources shortages, the forecast and determination of crop yield at regional scale has been considered as a strategic topic.

Climate change contributes to increase the uncertainty on crops yield, promoting the development of crop simulation models for yield assessment.

Yield estimation has been an important issue in irrigated crops, entailing the obtaining some indicators, as water productivity (WUE), essential for a correct water management.

In this study, a methodological proposal considering a simplified approach using a simplified optimized model (Aqua Crop) has been carried out. This model under semi-arid conditions for rain fed Sorghum located in five stations representing five regions of different climate characteristics in Sudan has provided very satisfactory results. Despite limitations of models, application of global climate models (for predicting climate data) and the crop growth simulation models (Aqua Crop) provide a more scientific approach to investigate the impact of climate change on crop production.

Application of Aqua Crop showed high grain yield gap between actual amounts and model predicted potential values which indicate that there is possible room to improve crop grain and biomass productivity. In its application to predict yield in the new climate regime, Aqua Crop demonstrated that crop producers may adapt to climate change by late planting of short season Sorghum cultivars.

Application of new technologies may assist in finding solutions to crop production under climate change conditions to improve food security.

The model results described accurately the observed temporal and spatial yield variability for both grain yield and biomass. This result indicate that Simple and empirical models using uniquely weather data are able to provide accurate yield estimations, even better than more complex and physically based models. WUE results were equally satisfactory, obtaining some indicators, as water productivity (WUE), essential for a correct water management.

5.2 Conclusions:-

1 Study of Benchmarking yield gaps in rain fed agriculture and assessment of long-term productivity in rain fed agriculture in Sudan indicate that.

2 To decrease the gap between potential yield (grain and biomass) and actual obtained yield Aqua Crop model may be employed to help in identifying the possible underlying causes of the yield gap.

3 From the study of prediction of rain fed Sorghum crop grain and biomass yield at five regions representing different climate zones in Sudan under the prevailing climate conditions shows that:

   a. The annual variability of both grain yield and biomass follows the same trend.
   b. The farmers ’choice of sowing date can be an important adaptation strategy to climate change and this management options should be considered in climate change impact studies on agriculture.

4 The study on Rain fall water Use Efficiency (WUE) for regions of different climate element shows that WUE is lower in the driest regions and higher for those of high rain fall.

5.3 Recommendations

5.3.1 For Policy making

- Assuming that most of the institutional impediments can be overcome it is quite feasible to increase production and yields. The technology and agricultural practices required are well known and already used on a large scale world-wide and on some of the more advanced farms in Sudan, such as Agaadi. The ultimate improvement would be zero tillage also known as no till or conservation tillage.
- To introduce the new technology and agricultural practices will involve greater capital investments by farmers in terms of farm infrastructure, machinery and buildings and greater inputs would be required in terms of machinery, fertilizer, seeds, agro-chemicals and - importantly - farmer’s time. Support would be required for farmers: small farmers with a few feddans, medium enterprises of less than 1,000 feddans and larger farms up to 5,000 feddans.
- The central feature of the improved technology and agricultural practices would be moisture management. There would be an emphasis on: timeliness of operations, improved use of existing machinery, Improved use of purchased inputs, and improved cultural practices.
- There is potential to increase farm productivity by better exploitation of the scarce water in the dry season. It may be possible to increase farm incomes significantly by growing high value short-duration crop cultivars through improving water utilization efficiency by early crop planting to better use of early season soil water.

5.3.2 For Future Research

All the possibilities of Aqua Crop model have not yet been explored in this study, and it remains necessary to:

1. Evaluate and quantify the errors involved in Aqua Crop simulations.
2. Developing water production functions with Aqua Crop and using them in Decision Support Systems .
3. Using Aqua Crop for water allocation decisions at basin or regional levels .
4. Determining the seasonal water requirements and its components for various crops on a farm Developing deficit and supplemental irrigation programmers at a field scale influence of field management on rain fed agriculture .

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