PROSPECTS OF SUSTAINABLE UTILIZATION OF SUDAN WATER RESOURCES IN AGRICULTURE

By
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Faculty of Agriculture
University of Khartoum
December 2008
DEDICATION

To my kind mother

To my father

To my brothers and sisters

To my friends

And all those who helped me to finish this study
Acknowledgements

Thanks to Allah for his assistance to complete this work.

I would like to express my deepest thanks and appreciation to my supervisor Dr. Abd Elmoneim Elamin Mohamed for his generous assistance, keen interest and his useful guidance in this study.

My thanks are due to my family for their help and support.

My thanks are extended to my friends for their continuous encouragement.

My thanks are also extended to every one who contributed in the preparation of this thesis.
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Prospects of Sustainable Utilization of Sudan Water Resources in Agriculture

(M.Sc. Agric. Engineering Thesis)

By

Amir Khalid Basheer Ahmed

Abstract: This study was conducted at the Faculty of Agriculture, University of Khartoum during the period from November 2007 to July 2008. The objectives of the study were to assess the amount of water resources of Sudan and investigate the means and ways of sustainable development and the utilization of these resources for agriculture. Data was collected from dependable sources including the Ministry of Irrigation and Water Resources, the Information Center (IC) the Rural Groundwater Directorate, the International Water Management Institute, Food and Agriculture Organization of the United Nations, and the published literature about the topic. The available water of Sudan is estimated to be about 36 BCM. The Sudan share from the agreement between Egypt and Sudan in 1959 is 18.5 Billion Cubic Meters (BCM). Irrigated agriculture is believed to consume about 86% (15.92 BCM was consumed in season 2007), 14% for the other uses including human and animal and industry uses. The total demand of the water in 2030 is estimated to be 48.0 BCM. To achieve sustainable development a package of measure is therefore required to improve water resources uses in conservation, optimum development and protection. Water resources need to be accurately assessed to make plans for sustainable development and management. Sudan needs to cooperate with the different Nile basin countries in the future especially Egypt and Ethiopia to develop the basin by construction of dams. The seasonal streams represent a very important resource in Sudan if well developed. Use of water harvesting techniques in the rainfed sector will increase the productivity of crops. Managing and monitoring the groundwater and use of artificial recharge techniques is an option for storage and utilization. Future research should focus on water resources assessment, adoption of artificial groundwater techniques where applicable, adoption of irrigation management practices and introduction of modern irrigation systems where appropriate.
لدى الزراعة في السودان، فإن التحليل للإمكانات المائية في الزراعة هم جزءًا من أبحاث، ويعود تاريخها إلى عام 2007. الفترات الأولى بين عام 1959 وعام 2007، حسب المواطنين، كانت تتميز بالتهوي المائي، والذي يمكن أن يشتمل على أوقات في الربيع والخريف. وقدرت الزراعة بـ3689 متراً ميلاديًا في السودان، وبين التفاهمات، تعتبر نسبة 18.5 بالمئة من الموارد المائية، والتي تستخدم في الزراعة، 86%، بينما يكون النشاط الزراعي بالحيوانات وبيض الإنسان يعول عليه 15.92 متراً ميلاديًا. ويتطلب ذلك تحسين الظروف الصحية للمنطقة، وتحسين التنامي، وتحسين الوضع الأدبي للظاهرة الزراعية، حيث يمكن أن تتفاوت النتائج. يولد السودان، بناءً على تطوره، خصوصًا في نهر النيل ضمن دول، وقد يكون تحديًا للزراعة الحديثة، وهي تتمتع بتعليمات متنوعة، ويمكن أن تكون تكنولوجيا الزراعة الحديثة، وتكون متاحة، ولكنها تتم تنفيذها بشكل لم يسبق له مثيل. }

" Mrs. Amira Bishari Khald "

"Research Center: Faculty of Agriculture, Al-Qurtas University, 2007-2008. "

"This study was conducted during the period of August 2007 to February 2008. This study aims to provide information on the irrigation water resources in the Sudanese.
CHAPTER ONE
INTRODUCTION

Water is considered as the most important natural resource especially in the arid areas of the world. For stable agriculture and proper establishment of the urban centers the amount of water needed should be made available.

Water resources can be classified as conventional and non-conventional. Conventional water resources include surface water (permanent rivers, seasonal streams, lakes and khors), rain water and groundwater (renewable or fossil aquifers and permanent storage). Non-conventional water resources include reuse of sewage water, recycling of agricultural drainage water, and desalinization of seawater. While miscellaneous water resources include water transportation, iceberg utilization and dew harvesting.

The total global water (surface and groundwater) is estimated to be 1500,000 BCM from which: The Sea and Oceans water (saline water) 1445,000 BCM. Fresh water 45,000 BCM. Polar fresh water 37,000 BCM. Fresh water in rivers and lakes 1,155 BCM. Groundwater 6,930 BCM. Water infiltrated in the soil and living bodies 3,465 BCM.

Sustainable development and management of water resources can be categorized as follows:
- Water development and management practices (rainwater harvesting, conservation tillage in rainfed sector, seasonal water harvesting, artificial recharge of ground water, supplementary irrigation, iceberg utilization and dew and fog harvesting)
- Water conservation measures include increasing the storage capacity of the dams, reducing evaporating water surfaces, irrigation water management.
- Innovative irrigation methods and appropriate management at the on-farm level.

Sudan has a large arable area which constitutes about 36% of the total area of the country which amounts to about 600 million feddanns. The actual cultivated area is about 4.5 million feddanns under irrigation and about 25 million feddanns in the rainfed sector. The cultivated area is characterized by a remarkable low productivity. The growing scarcity and misuse of the available water resources of Sudan constitute challenges to water demands for various utilities. Major threats are facing sustainable agricultural development that accounts for about 80-85% of water consumption. Therefore there is a vital need if the Sudan is to increase the cultivated area by using sustainable development and management of water resources.

**Study objectives:**

1. Assessment of the conventional water resources of the Sudan.
2. Estimation of the amount of water actually utilized from the different water resources in Sudan and the demand in the future.
3. Suggestions of the methods which can lead to sustainable development and management of the conventional water resources.
CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction:
Sudan is the largest country in Africa and has a special geopolitical location bonding the Arab world to Africa south of the Sahara. It’s area is about 2.5 million km² extending between latitudes 4° N and 22° N and longitudes 22° E to 38° E. It extends from north to south to about 2000 km; while it extends from east to west to about 1500 km at its maximum. On the north –east it is bordered by the Red Sea and it shares common borders with nine countries: Eritrea and Ethiopia in the east, Kenya, Uganda and the Democratic Republic of Congo in the south, The Central Africa Republic, Chad and the Libyan Arab Jamahiriya in the west, and Egypt in the north. The country is dominated by gently sloping plains with the exception of Jebel Marra, the Red Sea hills, Nuba Mountains and Imatong hills. Its main features are the alluvial clay deposits in the central and eastern parts, the stabilized sand dunes in the western and northern parts and the red ironstone soil in the south.

Its current population is estimated to be around 32 millions. It has great potential for agriculture with it is vast flat and fertile lands. More than half that population lives on just 15% of the land which is the area neighboring the Nile. Most of the rest of the population live in towns and around water points away from the Nile (FAO, 2005).
2.2 Climate:
Sudan has tropical sub-continental climate, which is characterized by a wide range of variations extending from the desert climate in the north, through a belt of varying summer rainy season climate to the equatorial type of climate in the extreme south. The annual rainfall ranges between 25 mm in the dry north and over 1000 mm in the tropical rain forests in the south. The mean annual temperature ranges from 30 °C to 40 °C in summer and from 10 °C to 25 °C in winter. The rainy season is generally short extending for three to four months in most of the country. Potential evapotranspiration ranges from 3000 mm/year in the north to 1700 mm/year in the extreme south. The country has plenty of sunshine and vast productive lands estimated at 84 million hectares whereas the actual area under cropping has slightly exceeded 10% of the potential. Most of the agricultural activities are concentrated in the middle of the country, in the dry savannah zone with erratic annual rainfall of 300-600 mm over a period of three to four months (Eldaw, 2003).

2.3 Water resources of Sudan
The water resources of Sudan can be classified as follows:

2.3.1 Rainfall:
Rainfall varies from practically no rain in the desert zone in the north to 1000 mm in the extreme south (Eldaw, 2003). The country can be divided into three zones according to rainfall regime. The annual rainfall in the northern half of Sudan varies from 200 mm in the center of the country to 25 mm northwards towards the border with Egypt. Where it rains, the rainy season is limited to 2 to 3 months with the rest of the year being virtually dry. Rainfall usually occurs in isolated showers, which vary considerably in duration, location, and from year to year. The coefficient of variation of the
annual rainfall in this northern half of the country could be as high as 100 percent. In the quarter south of the center of the country, the annual rainfall exceeds 700 mm, and is concentrated in only four month, from July to October. The average annual rainfall of the region is between 300 to 500 mm. Rainfed agriculture in Sudan is mainly practiced in this quarter. As the coefficient of variation in annual rainfall in the region is around 30 percent and the dry season extends for about eight months, the area cultivated and the productivity vary widely from one year to another. In the most southern quarter of the country, the annual rainfall exceeds 700 mm and can reach 1600 mm. This area is dominated by extensive wetlands. Some parts are infested by insects which are hazardous to humans and livestock (FAO, 2005).

Rainfall can be also classified according to Abdalla and Osman (1983) into the following zones:

a- The desert zone, north of latitude 17° N with annual rainfall less than 75 mm.

b- The semi desert zone between latitudes 15° and 17° N with annual rainfall of 75 to 300 mm.

c- The Savanna zone between latitudes 9° and 15° N with annual rainfall of 300 to 800 mm.

d- The flood plains and equatorial forests south of latitude 9° N with annual rainfall of more than 800 mm.

The major issue to be highlighted is that the rainfall in the country is characterized by its spatial and temporal variability. In general the average annual rainfall in Sudan is about 416 mm. The erratic nature of the rainfall and its concentration in a short season places Sudan in a vulnerable situation (FAO, 2005).
The amount of the annual rainfall is about 1000 BCM. It worth’s noting that the amount of rainfall decreased in the last 30 years about 10 mm in the northern portion and 150 mm in the southern portion of the country (Farah, 1999).

2.3.2 Surface Water:

The surface water can be classified as follows:

2.3.2.1 Nilotic Water:

The Nile with its main tributaries (White Nile, Blue Nile and Atbara River) is the world’s longest river. It flows 6,600 kilometer, traversing more than 35 degrees of latitude and drains an area of about 3.1 million km², one-tenth of Africa continent. It is generally agreed that the Nile has several sources. The principal streams are the White Nile, which begins in the great Lakes region of central Africa; and the Blue Nile and the Atbara, both flowing from the highlands of Ethiopia. The Nile’s most distant source is the Kagera River, which flows from Burundi through Rwanda and Tanzania into Lake Victoria (NGUW, 2001).

Rainfall over the central Africa Plateau (Equatorial Lakes) and over the Ethiopian highlands is the main source of River Nile system and other transponder seasonal streams such as Gash and Baraka (FAO, 2005).

It is worth noting that the flow contribution of the main tributaries of the Nile River from the Ethiopian highlands is 86% (Blue Nile 59%, Baro-Adobo 14% and Tekezze- Atbara 13%) and that from equatorial lakes is 14%. During flooding (July to October) over 90% of the Nile flow is from Ethiopia and less than 10% from the Equatorial Lakes (Eldaw, 2003).

About 44% of the Nile basin lies in Sudan, while 80% of Sudan lies in the Nile Basin (FAO, 2005). Ten countries share the Nile, which dominates the map of Sudan. These are: Burundi, Democratic Republic of Congo, Egypt,

There are certain international agreements controlling the relationships between these countries since 1891 up to 1959. The most important agreements between these countries as mentioned by Mahadi (2000) include the following:

- The 1891 Agreement between Britain and Italy
- The 1902 Agreement between Britain and Ethiopia
- The 1906 Agreement between Britain and Congo
- The 1929 Agreement between Britain and Egypt
- The 1959 Agreement between Sudan and Egypt.

The first Nile Water Agreement between Sudan and Egypt was signed in 1929. It gave Egypt the right to use 48 BCM/year, while it gave Sudan the right to tap only 4 BCM/year. The treaty did not allocate to Ethiopia any rights to use the Nile waters and still bound Uganda, the United Republic of Tanzania and Kenya and barred them from using the Lake Victoria waters (FAO, 2005).

The Sudan’s share of the Nile water, according to the 1959 Nile Water agreement between Egypt and Sudan is 18.5 BCM/year as measured at Aswan (20.5 BCM/year as measured at Sennar), and the corresponding share for Egypt is 55.5 BCM/year (Ali, 1993).

2.3.2.1.1 Blue Nile:

The Blue Nile and its tributaries all arise from the Ethiopian Plateau at an elevation of 2,000 to 3,000 meter above m.s.l, which is generally considered the source of the Blue Nile. The river has cut a deep gorge through the Ethiopian Plateau, which is in some places 1,200 meter below the terrain level on either side. Numerous rock-outcrops occur in the river bed, the last
of which are a few kilometers south of Roseires, some 1,000 km from its source beyond Lake Tana, and known as the Damazin rapid. The Blue Nile emerges from the Plateau close to the western border of Ethiopia, where it turns North-west and enters the Sudan at an altitude of 490 meters above m.s.l. Just before crossing the frontier, the river enters the clay plain, through which it flows over a distance of about 735 km to Khartoum. At this point, the Blue Nile joins the White Nile to form the main stem of the Nile River. The average slope of the river between Lake Tana and the Ethiopia frontier is about 1.6 m/km. From the frontier to Khartoum, the slope is much less, about 15 cm/km. Downstream of the frontiers two tributaries of some importance join the Blue Nile in the reach between Sennar and Wad Medani namely the Dinder and Rahad rivers. Both rivers originate from the Ethiopian Plateau, about 30 km west of Lake Tana. They are seasonal streams, reduced to pools in the dry season.

The Blue Nile Basin, including the Dinder and Rahad Basins, has a catchment area of 324,530 km². The greater part of these catchments is located in Ethiopia (FEWS, 1992). The flow of the Blue Nile reflects the seasonality of rainfall over Ethiopian highlands where the two flow periods are distinct. The flood period or wet season extends from July to October, with the maximum in August-September, and low flow or dry season from November to June. Therefore the annual Blue Nile hydrograph has a constant bell-shaped pattern, regardless of variation in the annual flow volumes. The average annual flow of the Blue Nile and its tributaries to the confluence with the White Nile at Khartoum is about 50 BCM; the daily flow fluctuates between 10 million m³ in April to 500 million m³ in August (FAO, 2005).
The total annual average supply of Dinder tributary is 3 BCM flowing from June to December while that of Rahad tributary is 1.09 BCM flowing during the same period (Ali, 1993).

2.3.2.1.2 White Nile:
The total annual average supply of the White Nile system as measured at Jebel Aulia Dam is 30.9 BCM, with a daily flow fluctuating from 54 million m$^3$ in April to 114 million m$^3$ in November. The total annual average supply of Bahr El Ghazal basin system is 14 Mm$^3$, but this supply is substantially lost in swamps, save for 0.5 BCM only which reaches the White Nile. These swamps cover an area of 40,000 km$^2$ and are subjected to a rainfall of 900 mm and evaporation rate of 1200 mm annually.

The total annual average supply of Bahr El Jebel Basin is 29 Mm$^3$ at Mongalla, but due to the huge losses in Bahr El Jebel swamps, the volume reaching Malakal is only 14.7 BCM. Bahr El Jebel swamps cover an area of 7,000 km$^2$. The total annual average supply of the Sobat Basin at Malakal is 13.7 BCM with a daily discharge fluctuating between 8 million m$^3$ in April to 66 million m$^3$ in November. The total water losses due to spillage into the swamps in this basin amounts to 4 BCM annually in the Baro tributary and another 4 Mm$^3$ in the Machar marches which cover an area of 20,000 km$^2$ and with annual rainfall of 800 mm (Ali, 1993).

2.3.2.1.3 The Atbara River:
River Atbara, which is the last tributary of the Nile, enters the Main Nile at about 320 km downstream of Khartoum. It is 880 km long and its catchment area amounts to 112,400 km$^2$, the greater part of which is found in Ethiopia. The main tributary of the Atbara is the Setit River, with a catchment area of 69,000 km$^2$. The Atbara is more strongly seasonal in its flow compared to the Blue Nile. Over its first 300 km the slope of the Atbara is very steep, i.e.
about 5 m/km. The steep slope in its upper reach is responsible for the excessive sediment load in proportion to its flow volume (FEWS, 1992). The steep slope and the small catchment area of the river reflect the rainfall over the upper catchments as runoff at Sudan border within one to two days (FAO, 2005). The total annual average supply of River Atbara is 12 BCM of which 7 BCM come from Setit tributary and 5 BCM from Atbara branch. The flow is between June and February (Ali, 1993).

2.3.2.1.4 The Main Nile:

The reach of the Nile down stream of the confluence of the Blue Nile and the White Nile Rivers is known as the Main Nile (FAO, 2005). At Khartoum the Blue Nile joins the White and the combined water flows for some 1,850 km to Aswan. The course of the river consists of a series of placid reaches of mild slope, separated by rocky rapids, called the cataracts, where the slope is greater and the flow is more turbulent. The downstream boundary of the flood forecasting model is located at Dongola. The overall average slope between Khartoum and Dongola is of the order of 12 cm/km. Forecasts are made for a period of ten days. This is approximately the lead time between rainfall events over the upper catchments and the rise in water level at Dongola on the Main Nile in the north of the Sudan. The lead time for Khartoum is approximately six days. About three days are gained by runoff forecasting for the upper catchments of the Blue Nile and Atbara rivers (FEWS, 1992). The annual flow is different from year to year (Table 2.1). A low level of flow of 42 BCM was reached in 1913, but in 1964 reached 120 BCM (Mohamed et al, 2006).
Table 2.1 The River Nile discharge at Dongola in BCM from 1987 to 2006.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Q BCM</th>
<th>Year</th>
<th>Total Q BCM</th>
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<tr>
<td>1987</td>
<td>46.296</td>
<td>1997</td>
<td>64.993</td>
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<td>1988</td>
<td>92.230</td>
<td>1998</td>
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<td>1999</td>
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<td>1990</td>
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<td>1995</td>
<td>58.529</td>
<td>2005</td>
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</tr>
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<td>1996</td>
<td>79.624</td>
<td>2006</td>
<td>81.033</td>
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</tbody>
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Source: MIWR (2006)
Table 2.2 The annual discharge of the Nile and tributaries in some years in BCM.

<table>
<thead>
<tr>
<th>Type Of Year</th>
<th>Year</th>
<th>Blue Nile Deim</th>
<th>Dinder Giwasi</th>
<th>Rahad Hwata</th>
<th>Atbara Upper Atbara</th>
<th>White Nile Malakal</th>
<th>Main Nile Dongola</th>
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<tbody>
<tr>
<td>Dry</td>
<td>1984</td>
<td>29.733</td>
<td>0.351</td>
<td>0.291</td>
<td>4.944</td>
<td>26.269</td>
<td>42.122</td>
</tr>
<tr>
<td>Medium</td>
<td>1995</td>
<td>37.126</td>
<td>1.475</td>
<td>1.037</td>
<td>11.561</td>
<td>28.714</td>
<td>58.529</td>
</tr>
</tbody>
</table>

2.3.2.2 Non-nilotic water:

In the Sudan the following watersheds can be recognized:
- Nuba Mountains (south west)
- The Red Sea Hills (east)
- Angasana Hills (south east)
- Jebal Marra (west)
- Al Botana Hills (central)
- The Ethiopian Plateau (Baraka and Gash)

Each watershed system of the above is comprised of many wadis and khors of various sizes ranging from large ones of annual discharge of up to 100 million cubic meters to small ones of annual discharge of less than one million cubic meters (Abd Algadir et al., 2003).

The major streams are the Gash and Baraka in the east of the country, both of which are characterized by large variations in annual flow and heavy silt loads (FAO, 2005). The Gash catchment area is mainly in Eritrea, south of Asmara and covers a distance of approximately 350 km upstream of Kassala. The slope of the river is high (above 1 m/km) and flow velocities of up to 3 m/s are observed at Kassala when the river is in spate. This suggests that the time lapse between the occurrence of rain and the arrival of the related flow at Kassala could well be in the order of 24 hours. Rainfall forecasting may add at least one day of fairly reliable flow forces. Flow variations within the day are substantial and water-level observations are made every three hours during floods.

In Jebel Marra region, where numerous seasonal wadis flow, there are 32 stream gauging stations in catchment areas totaling 32,000 km² and hence an average density of one station per 1,000 km² which tallies with the adopted standards (FEWS, 1992).
The amount of rainfall, general terrain characteristics, vegetation cover and geographical location influence considerably the distribution of major watershed systems in the Sudan. Part of it spread until it vanishes within the territory and part of it crosses the boarders such as Azoom and Kaja, which cross to Chad. Gauging of some of these wadis shows that there is diversity in the amount of discharge. They vary from less than one million cubic meter to more than one hundred million cubic meters per annum. Therefore, three categories can be recognized based on the amount of discharge as follows:

a- Wadis of discharge of more than one hundred million cubic meter: examples of such large wadis are wadi Ibra, Al Hamra, Shari, and Azoom all in Darfur region.

b- Medium wadis of discharge of 30 to 100 million cubic meters: examples of these wadis are wadi Shalango, Abu Habil in Kordofan; Um Hugara, Bulbul, Kaya and Nyala in Darfur; Awaiab in Nile State, Arbaat in Red Sea State and As Sumaa in Blue Nile State.

c- Wadis of discharge of 10 to 30 million cubic meters: examples of these wadis are wadi Kaja, Dagris, El Ku in Darfur and El Bardab, Hager Almake in Kordofan.

d- Wadis of discharge of less than 10 million cubic meters: examples of such wadis are Al Hawad and El Mukabrab in River Nile State and Goub, Khor Arab in Red Sea State.(Abd Algadir et al., 2003).

The average annual yield of the Non-Nilotic streams is estimated at about 7 Mm³, of which 5 Mm³ are internally produced (FAO, 2005).

2.3.3 Groundwater:

Groundwater constitutes the main water supply source for drinking and domestic use for more than 80% of human population, and their livestock in
the country. Groundwater is found under about 50% of the country's area (Kheralla, 1984). The extent of depth ranging from 40 to 400 meters and have total dissolved solids ranging from 100 to 2000 ppm. The Sedimentary Nubian Sandstone and Umm Ruwaba Formation are the main aquifers in Sudan (Eldaw, 2003). Groundwater is also very important for maintaining the environment through sustaining stream flows, wetland and support the vegetation among other things (Tinndimugaga, 2002).

**Groundwater Basins:**

The groundwater basins of Sudan are either in a simple form or in a complex one, according to their geological formations. There are six basins in the Nubian Sandstone formation, two in the Nubian / Umm Rwaba formation, eight in the alluvial deposits, two in the Umm Rwaba formations and two in the Nubian / Basalt formation (Salama, 1979).

2.3.3.1 The Nubian Basin:

The Nubian basin occupies 28.15% of the country area. Its water is of high quality and suitable for human and animal consumption. The basin is shared with Egypt and Libya (FAO, 1997). The Nubian basin is divided into the following:

a. Sahara Nile Basin:

The basin extends from North Khordofan State to the Egyptian border (FAO, 1997). It covers an area of 27,398 km². It is separated from the Sahara Nubian basin by a Basement ridge extending in a north eastern direction. The water level ranges from 10 meters near the Nile and falls rapidly moving away from the source of recharge. It reaches a maximum depth of 25 meters in the central part of the basin (Salama, 1979). The groundwater movement is from south to north, with a velocity ranging from 0.44 to 1.46 meter/year. The main source of recharge is from River
Nile, together with the under flow from the Blue Nile Basin. The water quality of this basin has a total dissolved solids ranging between 200 and 400 ppm. The salinity increases in the direction of groundwater away from the recharge source (Salama, 1979).

b. **Sahara Nubian Basin:**
This covers the northern part of northern Darfur State extending from the Tagabo-Meidob groundwater divide up to the Egyptian border (FAO, 1997). It covers an area of 324,656 km². The chemical quality of water ranges from 500 to 800 ppm. The water levels range from 10 to 50 meters. The water is flowing in two locations: - El Natron Oasis. - Nukhiela Oasis.

The groundwater movement is from the south to north with velocity ranges from 0.4 to 2.1 meter/year. The saturated thickness of the aquifer ranges from 100 to 1000 meters. The water is recharged mainly from rain that falls occasionally which seeps through cracks and joints, and accumulates in fans (e.g. wadi Hawar) and wadi deposits (e.g. Nakhiela and Natron). The amount of water recharged annually is estimated to be 20.6 million cubic meters, and the water under permanent storage is 9740 million cubic meters (Salama, 1979).

c. **Central Darfur Basin:**
The Central Darfur basin covers the area of the central part of Darfur and the western part of North Khordofan. It extends southward from Tagabo-Maidob groundwater divide, and is connected to the Baggara Basin in the south. Its surface area is 52,924 km². The water quality has total dissolved solids ranging from 100 to 400 ppm. In the northern part of the basin the water quality is very good; at some localities it does not exceed 80 ppm. In
Jebel Hilla area in the southern part of the basin salinity reaches up to 1800 ppm (Salama, 1979). The water level ranges from 25 to 100 meters below the soil surface (FAO, 1997). The groundwater movement is from the north to the south east with a velocity of 0.3 to 6.0 meter/year. The saturated thickness ranges from 100 to 350 meters, the amount of annual recharge is 47.6 million cubic meters, this basin is connected to the Baggara Basin in its southern part and the amount of out flow is estimated to be 12.8 million cubic meters. The amount of water under permanent storage is 794 million cubic meters and the abstraction rates are 5.63 million cubic meter/year.

d. Nuhud Basin:
This basin is isolated from the Nubian Sand Stone. It covers parts of the central part of Northern Khorodfan State (FAO, 1997). Covering an area of 6,798 km². The chemical quality of the water is low. Total dissolved solids being about 500 ppm. The saturated thickness of the aquifer ranges from 150 to 250 meters. The annual recharge is estimated as 15.4 million cubic meters (Salama, 1979). The water level ranges from 75 to 100 meters below the soil surface and the water quality is low (FAO, 1997). The direction of groundwater flow is from west to east with a velocity of 1.0 to 2.75 meter/year (Salama, 1979).

e. Sag El Na’am Basin:
This basin covers a trough, which extends along wadi El Ku, 40 kilometers south El Fashir town, capital of North Darfur State, covering an area of 2,678 km². It is connected to central Darfur Basin through a narrow straight. The chemical quality of water is good as it has low values of total dissolved solids ranging from 80 to 500 ppm.; the Sodium adsorption ratio (SAR) ranges from 1.08 to 3.5. The depth to water level ranges from 50 to 1000 meters. The water is under free water table conditions on the fringes of the
basin. Whereas in the central part of the basin the mudstone layer is usually 15 m thick, the water level is under semi-artesian pressure. The ground water movement is from north to south and south east with velocity ranging from 1.0 meter/year on the south part of the basin to 25 meter/year in the central and eastern parts. The saturated thickness ranges from 500 to 2000 meters. The exploitation of the basin for irrigation purposes was being developed. Due to the deep water levels the economic feasibility of the irrigation is rather doubtful, but is estimated for many reasons as profitable (Salama, 1979).

f. River Atbara Basin:
It extends north to Abu Haraf water divide up to Atbara River covering an area of 23,896 km², and is bounded by the River Nile from the west and the Basement from the east. The water level ranges from few meters near the Nile and River Atbara, but drops away from source of recharge and reaches down to 100 meters. The saturated thickness ranges from 100 meters in the northern and western parts of the basin, and reaches 500 meters in the central part where a mudstone of thickness of 50 to 250 m layer is found. After the construction of Khshm El Girba dam in the upper part of River Atbara, the flow in the lower part becomes seasonal only during the floods. This greatly affected the life of the citizens, and the development of the groundwater resource becomes a necessity. It is expected that some 100,000 feddans will be irrigated from the groundwater resources (Salama, 1979).

2.3.3.2 Umm Rwaba Basin:
This basin can be divided into the following:

a. Sudd Basin:
This is the largest basin area in Sudan. It covers an area extending south ward from south of Bahar El Arab in the southeast direction down to Juba
and north east of El Runk (FAO, 1997). It covers an area of 365,268 km². Two major basins are connected to this aquifer and their outflow recharges the basin:

i. The Baggara Basin in the western part of Sudan, and,

ii. The Eastern Kordofan in the central part of Sudan.

The Sudd Basin is a closed basin; water is flowing into this basin from the Baggara basin north of Bahar El Arab and from Umm Ruwaba Basin north of Rank area, in addition to the groundwater of the Sudd Basin flowing to its central part. The groundwater levels in the central part of the basin intersect the surface contours of lower elevations, indicating the possibility of the discharge from the aquifer to the streams and lake in the Sudd area. The groundwater flowing into the central part of the basin is some 200 million cubic meters; the major part of this water is believed to be discharged to the surface. The water levels are near to the surface, they range from 10 to 25 meters. The groundwater movement is towards the central part of the basin. The velocities range from 0.1 to 1.8 meter/year, which when compared to the velocities of the other basins is very slow. The chemical quality of the water is variable; it ranges from 200 to 500 ppm. In the peripheral zones of the basin. The salinity increases gradually with distance and depth. In the central part of the basin where the current is sluggish the salinity jumps to 5000 ppm. The annual recharge is some 341 million cubic meters. The amount of water under permanent storage is 11,000 million cubic meters, and the abstraction rates are 1.8 million cubic meters. The saturated thickness is between 100 to 3000 meters (Salama, 1979).

b. Eastern Kordofan Basin:

The basin covers the central part of Northern Kordofan State extending in a southeast direction from north El Obied down to the White Nile, occupying
20.5% of the area of the country (FAO, 1997). The basin is covering a NW-SE trough of a maximum thickness of two kilometers. The surface area of the basin is 68,392 km². The chemical quality is hard with total dissolved solids between 500 to 600 P.P.M in Bara region and it is high in the other parts of the basin ranging from 1000 to 5000 ppm. The water level ranges from 50 to 75 meters in the northern parts of the trough. The velocity of the water is slow, between 0.1 to 0.3 meter/year due to the small values of permeability and sluggish gradient. The saturated thickness ranges between 100 and 500 meters. The annual recharge is some 15.0 million cubic meters, the basin storage is about 1,710 million cubic meters while the abstraction rates is about 4.5 million cubic meters, which is high. The main recharge is from the White Nile and also from the surface flow during the rainy season (Salama, 1979).

2.3.3.3 Nubian / Umm Ruaba Basin:

This basin can be divided into the following sub-basins:

a. Baggara Basin:

It covers nearly the whole area of southern Darfur and the western part of southern Kordofan (FAO, 1997). The basin area is about 141,316 km². The chemical quality is varying as the basin consists of Nubian and Umm Ruwaba formations. In the east and west the total dissolved solid is low (100 to 400 ppm), while in the center it reaches up to 800 ppm. The water level ranges from 30 to 75 meters, the deepest water levels are in the central part of the aquifer. The saturated thickness is varying from 100 to 2000 meters. Groundwater is moving from the north, east and west towards the central part of the aquifer. From there the ground water moves in a south eastern direction towards the Sudd Basin. The velocities range from 0.13 to 1.75 meter/year. The annual recharge is some 155 million cubic meters; the basin
storage is 7110 million cubic meters while the abstraction rates are about 11.9 million cubic meters. The recharge is being mainly from northern, eastern and through the superficial deposits and wadi fill deposits (Salama, 1979).

b. Blue Nile Basin:
It covers the area between River Rahad and the Blue Nile (FAO, 1997). It extends in NW direction along the Blue Nile up to Khartoum and is bordered from the north east by Abu Haraf water divide and from the west by the White Nile, extending over an area of 75,808 km². The chemical quality of the water is varying. The total dissolved solids are low along the Blue Nile ranging from 300 to 500 ppm. The water level ranges from few meters near the river down to a maximum of 50 meters away from the stream. The direction of groundwater flow is paralleled to the direction of the surface runoff, i.e. the recharge from the rivers. The saturated thickness ranges from 100 to 500 meters. The average velocity is from 1 to 2.5 meter/year. The basin storage is about 70.9 million cubic meter/year (Salama, 1979).

2.3.3.4 Nubian / Basalt Basin:
This basin can be divided into the following sub-basin:

a. Gadaref Basin:
The basin covers the central part of Kassala State extending over an area of 28,016 km². The water chemistry is good with low values of the total dissolved solids ranging from 400 to 500 P.P.M. The water levels range from 50 to 75 meters, the water is moving in a North West direction with a velocity of 0.3 to 3 meter/year. The basin storage is about 700 million cubic meter/year; the annual recharge is 41.7 million cubic meter/year, while the abstractions rate is 1.2 million cubic meter/year. The saturated depth of aquifer ranges from 200 to 500 meters. The recharge is mainly from the
seeping into the sandstone formation from River Setit, (branch from River Atbara). The basin is receiving some under flow from adjacent basins in the borders; this amount is estimated to be 12 million cubic meter/year (Salama, 1979).

b. Shagara Basin:
The smallest basin in Sudan which covers the area west of El Fasher town up to Jebel Marra (FAO, 1997). It covers an area of 824 km². Water levels are near the surface, about 25 meters. The saturated thickness of the aquifer ranges between 200 to 300 meters. The recharge is from surface flow during the rainy season. The basin storage capacity is 4.5 million cubic meters; the annual recharge is about 1.1 million cubic meters, while the abstraction rate is 0.7 million cubic meters (Salama, 1979).

2.3.3.5 The Alluvial Basins:
The major alluvial basins are seasonal streams (khors). The runoff in those streams does not exceed three months/year. The run off during this period is substantial, and the aquifers are completely recharged after the rainy season. The alluvial deposits are characterized by high transmissivity values and storability figures. The shallow depth enabled the natives to develop their own technology of abstracting water for irrigation purposes. Those basins are the oldest known cultivation centers from groundwater resources (Salama, 1979).
CHAPTER THREE
METHODOLOGY

This study was conducted for the purpose of the assessment of Sudan water resources, the current situation of utilization of these resources the future demands and the prospects of the sustainable development. The information on water resources of Sudan was collected from published literature and from dependable sources. These sources include Ministry of Irrigation and Water Resources (MIWR), Food and Agriculture Organization of the United Nation (FAO), Institute of Irrigation Water Management (IWMI), Information Center (IC) in the Rural Groundwater Directorate, Seasonal Wadis Director and Water and Land Research Center. Conference papers on the topic were also cited. The information gathered were presented in this study in such a way as to give a clear picture on the amount of water available, future needs and the prospects of sustainable utilization and development especially for agriculture as it is the main user of water resources in Sudan. The international water issues concerning Sudan were also highlighted. The collected information was interpreted in such a manner as to encourage research work in this challenging area at present and in the future.
4.1 Water availability and future needs:
The current annual amount of water available to Sudan from all internal and external sources is about 30 BCM (Table 4.1). The Sudan’s share in the Nile water according to the 1959 agreement with Egypt as measured in central Sudan is 20.5 BCM, the average flow of non Nile streams is 5.5 BCM, and the renewable groundwater is estimated as 4.0 BCM (Eldaw, 2003).
The average annual rainfall is 416 mm, but ranges between 25 mm in the dry north and over 1800 mm in the tropical rain forests in the south (FAO, 2005).
The mean temperature ranges from 30 °C to 40 °C in summer and from 10 °C to 25 °C in winter. The potential annual evapotranspiration ranges from 3000 mm in the north to 1700 mm in the extreme south. The major limiting factor for agricultural production is the short duration of the rainy season and the erratic nature of rainfall during the growing period (FAO, 2005).
Sudan’s total natural renewable water resources are estimated to be 149 BCM/year, of which 30 BCM/year are internally produced. In a 10th frequency dry year, the internal water resources are reduced to about 22.3 BCM/year. Of the internal water resources, 28 BCM/year are surface water and 7 BCM/yr are groundwater, while the overlap between surface water and groundwater is estimated at 5 BCM/year. As a result of the Nile waters agreement with Egypt the total actual renewable water resource of the country amounts to 64.5 BCM/year (FAO, 2005).
As the rate of growths in population is estimated to be 2.7% annually, and the need for water increases with development at a higher growths rate. Therefore any potential increase from water development will be consumed. Expectations of the other Nile countries and those sharing non-Nile streams with Sudan might influence the amount of water available and its distribution in the region (Eldaw, 2003).

4.2 International Water Issue:
Surface water and ground water are mostly shared with neighboring countries. The River Nile, which is shared between 10 countries, is the primary source of Sudan’s dependable water. The four main non-nilotic streams are also shared with neighbouring countries. The largest groundwater aquifer, the Nubian Sandstone, is shared with Chad, the Libyan Arab Jamahiriya and Egypt.

The first Nile water agreement between Egypt and Sudan was signed in 1929. It allocated to Egypt the right to use 48 BCM/year, while it gave Sudan the right to tap only about 4 BCM/year. The treaty did not allocate to Ethiopia any rights to use the Nile waters and also still bound Uganda, Tanzania and Kenya and bars them from using Lake Victoria Waters. In 1959, the Nile waters agreement between Egypt and Sudan assigned to Sudan 18.5 BCM/year, measured at Aswan at the border with Egypt. The other river nations are still not included in this agreement (FAO, 2005).
<table>
<thead>
<tr>
<th>Water resource</th>
<th>Quantity (Billion Cubic Meter)</th>
<th>Limitations and constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudan share from Nile</td>
<td>20.5</td>
<td>High seasonality, requires storage facilities</td>
</tr>
<tr>
<td>Streams (other than the Nile system)</td>
<td>5 - 7</td>
<td>High seasonality, requires storage facilities</td>
</tr>
<tr>
<td>Groundwater</td>
<td>4.0</td>
<td>High cost for exploration and extraction, requiring advanced technology</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>36.0</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 The Total Groundwater in Sudan

<table>
<thead>
<tr>
<th>Ground basin</th>
<th>Area km²</th>
<th>Quantity of water BCM</th>
<th>Annual average recharge million m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian basin</td>
<td>637073</td>
<td>12600</td>
<td>1008</td>
</tr>
<tr>
<td>Umm Ruewaba basin</td>
<td>660957</td>
<td>4150</td>
<td>586</td>
</tr>
<tr>
<td>Nubian/Basalt Basins</td>
<td>3.42</td>
<td>715</td>
<td>325</td>
</tr>
<tr>
<td>Alluvial basins</td>
<td>-</td>
<td>2.5</td>
<td>1800</td>
</tr>
<tr>
<td>Total</td>
<td>16757</td>
<td></td>
<td>4109</td>
</tr>
</tbody>
</table>

Source: Abd Alkaber (2006)
4.3 Nile Basin Initiative:
Recently, the Nile Basin Initiative has been created and prepared as a Strategic Action Programme, which consists of two sub-programmes: the Shared Vision Programme (SVP) and the Subsidiary Action Programme (SAP). The SVP is to help create an enabling environment for action on the ground through building trust and skill, while the SAP is aimed at the delivery of actual development projects involving two or more countries. Projects are selected by individual riparian countries for implementation and submitted to the Council of Ministers of the Nile Basin Initiative for approval.

Sudan, Ethiopia and Egypt have also adopted a strategy of cooperation in which all projects to be launched on the river should seek the common benefit of all member states and this should be included in accompanying feasibility studies (FAO, 2005).

4.4 Water use:
Sudan population in 2002 was estimated to be 32 millions. The sum of internal and external water resources available to Sudan is about 30 BCM. This shows that Sudan is already below the water stress margin of 1000 m$^3$ per capita per year. The actual per capita per year consumption is much less than 1000 m$^3$ as the water used fluctuates between 14 and 18 BCM out of the 30 BCM. This is mainly because of the varying nature of rain and flow of the Nile and the non-Nile streams coupled with limited available storage capacities, which are continuously decreasing by silt accumulation. The actual per capita consumption of water is just over 500 m$^3$ per year, way down in the water stress zone. The remaining shares of the Nile waters and the available non-Nile and renewable ground water are all committed to be studied, to irrigate the highly fertile land awaiting the availability of enough
storage capacities and pumping facilities. The current situation is that irrigated agriculture (Table 4.3) consumes about 94% of the water, 5% goes to human and animal consumption and 1% to industrial and other uses (Eldaw, 2003). Also FAO assessed the use of water in year 2000. The total water withdrawal in Sudan was estimated at 37 BCM for the year 2000. The largest water user by far was agriculture with 36 BCM. The domestic sector and industry accounted for 0.99 BCM and 0.26 BCM, respectively. Water used in Sudan is derived almost exclusively from surface water resources. Groundwater is used only in very limited areas, and mainly for domestic water supply (FAO, 2005).
Table 4.3 Main Irrigation Schemes in Sudan and their Water Consumption

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Cropping area 1000 Fadden</th>
<th>Year of development</th>
<th>Water consumption BCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gazira and Managil</td>
<td>2.2</td>
<td>1925-1957</td>
<td>7.598</td>
</tr>
<tr>
<td>Blue Nile pump scheme</td>
<td>616</td>
<td>1925</td>
<td>2.571</td>
</tr>
<tr>
<td>White Nile pump scheme</td>
<td>620</td>
<td>1935</td>
<td>2.840</td>
</tr>
<tr>
<td>New Halfa</td>
<td>447</td>
<td>1959</td>
<td>1.700</td>
</tr>
<tr>
<td>Rahad</td>
<td>300</td>
<td>1977</td>
<td>1.139</td>
</tr>
<tr>
<td>Suki</td>
<td>90</td>
<td>1971</td>
<td>0.330</td>
</tr>
<tr>
<td>Kenana</td>
<td>80</td>
<td>1978</td>
<td>0.838</td>
</tr>
<tr>
<td>Asalaya</td>
<td>37</td>
<td>1976</td>
<td>0.448</td>
</tr>
<tr>
<td>Asalaya</td>
<td>37</td>
<td>1976</td>
<td>0.448</td>
</tr>
<tr>
<td>Guneid</td>
<td>80</td>
<td>1953</td>
<td>0.540</td>
</tr>
<tr>
<td>West Sinnar</td>
<td>32</td>
<td>1977</td>
<td>0.388</td>
</tr>
<tr>
<td>Abu Naama</td>
<td>30</td>
<td>1975</td>
<td>0.11</td>
</tr>
<tr>
<td>Seyal-Kelli</td>
<td>17</td>
<td>1974</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>4,412</td>
<td></td>
<td>18.882</td>
</tr>
</tbody>
</table>

Source: Basheir (1985)
4.5 Water Storage Facilities:
Dams in Sudan were constructed to provide water for irrigation during the low season period (Table 4.4).
- These dams have different and limited storage capacities as follows:
  a. Roseiris dam has a present storage capacity of 2.0 BCM which is planned to be increased to 7.7 BCM by heightening the dam. It is a feeder dam.
  b. Sennar dam had a designed capacity of 0.93 BCM now reduced to 0.4 BCM. Sennar dam is mainly used for irrigating Gezira and Managial scheme.
  c. Girba dam had a capacity of 1.3 BCM now reduced to 0.65 BCM due to deposition of silt. It is used for irrigating New Halfa scheme.
  d. Jebel Aulia dam has a storage capacity of 3.5 BCM, but of limited use.
  e. Merowe dam will be constructed for hydro electric power and not for storage of water for irrigation purposes (Ali, 1993).
### Table 4.4 Dam Reservoirs Capacity

<table>
<thead>
<tr>
<th>Dam reservoir</th>
<th>Location</th>
<th>Construction Year</th>
<th>Capacity BCM</th>
<th>Present Capacity BCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sennar</td>
<td>Blue Nile</td>
<td>1925</td>
<td>0.93</td>
<td>0.4</td>
</tr>
<tr>
<td>Jebel Awlia</td>
<td>White Nile</td>
<td>1937</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Roseries</td>
<td>Blue Nile</td>
<td>1966</td>
<td>2.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Kashm El Girba</td>
<td>Atbra River</td>
<td>1966</td>
<td>1.3</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>8.23</strong></td>
<td><strong>6.65</strong></td>
</tr>
</tbody>
</table>

4.6 Hydropower and Energy:
In Sudan, there is a substantial hydropower prospect of generation with an estimated technically exploitable of some 4860 Mega Wat (Table 4.5). However Sudan potential could be doubled under favorable cascade of national and regional projects. A recent study on opportunities of Power Trade in the Nile Basin countries indicated that hydropower generation from Sudan would be an important basis from interconnection and power trade in the Basin. The development measured by population access to electricity indicator, for Sudan is as low as 15% and electricity consumption per capita is low as well (Eldaw, 2003).
Table 4.5 Sudan power and Energy Potentials

<table>
<thead>
<tr>
<th>Location</th>
<th>Power in MW</th>
<th>Energy (GMH)/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
<td>Feasible</td>
</tr>
<tr>
<td>River</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Nile</td>
<td>4481</td>
<td>2775</td>
</tr>
<tr>
<td>White Nile</td>
<td>2239</td>
<td>1585</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>1789</td>
<td>425</td>
</tr>
<tr>
<td>Atbara River</td>
<td>606</td>
<td>42</td>
</tr>
<tr>
<td>Other</td>
<td>195</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td>9,308</td>
<td>4860</td>
</tr>
</tbody>
</table>

4.7 Future Water Demands:
A study by the ministry of irrigation and water resources (MOIWR, 1998) projected the irrigation need to be 32.6 BCM by the year 2030. Human and animal usage and other domestic and industrial need were estimated to be about 7 BCM (Table 4.6). If the incremental rise in evaporation from water storage for the proposed hydropower dams is added (6.6 BCM), the total demand would be 46.2 BCM. This would be more than all the water available to Sudan including its share from the conservation of the southern swamps. It is assumed that all the water flowing in the seasonal streams is harvested, the groundwater is pumped to the limit of its recharge and the storage facilities are available for the entire share from the Nile water. In addition, Sudan population at that time is expected to be 56 millions. Even if the gap in water availability was bridged some low, the per capita water consumption would be 867 m$^3$ per year, still under the water stress margin. It should be noted that the above mentioned study assumed that the irrigated area would be 2.44 million ha which still is less than 4% of the arable land of the country. Sudan has got the potential to be the bread basket for its neighbours and possibly the world at large as it has a vast fertile arable land and human power to develop it. The limiting factor is the availability of water and the adequate storage facilities (Eldaw, 2003).
The Blue Nile irrigation area is about 3.024 million hectare, White Nile 0.276 million hectares, Atbara 0.400 million hectares, Main Nile 0.350 million hectares.
Table 4.6 Annual Projection of the Water Consumption by year 2030 in Sudan

<table>
<thead>
<tr>
<th>Year</th>
<th>Irrigation BCM</th>
<th>Water Supply BCM</th>
<th>Animal and other BCM</th>
<th>Total BCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>17.5</td>
<td>0.4</td>
<td>1.3</td>
<td>19.2</td>
</tr>
<tr>
<td>2010</td>
<td>27.1</td>
<td>1.1</td>
<td>3.9</td>
<td>32.1</td>
</tr>
<tr>
<td>2020</td>
<td>32.6</td>
<td>1.9</td>
<td>5.1</td>
<td>39.6</td>
</tr>
<tr>
<td>2030</td>
<td>40.3</td>
<td>2.9</td>
<td>5.3</td>
<td>48.0</td>
</tr>
</tbody>
</table>

CHAPTER FIVE
DISCUSSION

5.1 General:
River Nile represents the basic water source in Sudan used in agriculture while most surface water from seasonal streams is lost (FAO, 2005). The quantity of the annual rain fall is estimated to amount to 1000 BCM (Farah, 1999). The groundwater is estimated to be 16757 milliard cubic meters. These sources need developing and integrated management for sustainable utilization.

5.2 Surface water development and management:
The surface water of Sudan can be divided into:
- Nile water and
- Non-Nile water (Seasonal streams).

5.2.1 Sustainable development and management of Nile Water:
The Nile water development can be categorized into the following:
- Irrigation water management.
- White Nile water development.
- Cooperation between the Nile Basin countries (Blue Nile).

5.2.1.1 Irrigation water management:
The entire irrigation schemes in Sudan consume about 15.920 Mm³ in season 2005/2006 (MIWR, 2006). Geziera scheme covers about half the irrigated area of the country while the other half is divided between corporations and agricultural projects. This sector produces about 100% of the sugar 95% Cotton, 36% maize, 32% ground nut and all the vegetables and fruits (Farah, 1999). Productivity in the irrigated sector must be considered as per unit volume of water. The productivity for the used water
is not more than 0.2 kg/m³ as a mean for cotton, maize, ground nut and wheat while the international statistics indicates the possibility of getting more than 1 kg/m³. The low productivity might be attributed to the following:

i. The water doesn’t reach the farm in the required amount at the required time because of the canal weeds and clays sediments.

ii. The producers don’t follow the water use recommendations (Farah, 1999).

Extensive research was carried out to develop field irrigation techniques to increase irrigation efficiency and management practices which increase water use efficiency. Introduction of water stress tolerant crops and sound irrigation scheduling are some of the techniques to be tried. The research of irrigation management was focused on:

i. Determination of the critical irrigation period according to the physiological phase of plant growth.

ii. Determination of the crop water requirements.

iii. Development of the surface irrigation systems from the point of sound design to increase irrigation efficiency.

iv. Introduction of the modern irrigation methods (sprinkler – drip irrigation) especially in the light soils with high permeability which are not suitable for surface irrigation.

v. Follow a crop rotation system which fulfils the following objectives:
   - maintains the land fertility.
   - increase the efficiency of crop water use.
   - controls pests.

vi. Implement agricultural extension service to advice farmers to use irrigation water wisely with minimum losses.
vii. Sugar Beet is recommended instead of sugar cane which consumes high amounts of water.

viii. Land leveling should be precise especially in surface irrigation and crops of high water requirements such as sugar cane by using laser technique.

x. Increase the irrigation systems efficiency especially surface irrigation systems.

The research which was conducted was an effort for achieving important changes to have scientific methods to determine the water requirement during the different growth phases of the crops in Gezira (Farah, 1999).

a. Water stress effect on crop:

Many studies had been conducted on the effect of water stress on different crops according to the growth stage. The effect was clear in cotton crop (Barakat variety) when some irrigations were missed during the different stages (Table 5.1).
Table 5.1 Effect of missing some irrigation during the different growth stages of cotton (Barakat variety)

<table>
<thead>
<tr>
<th>Date of missing irrig</th>
<th>Productivity Con./fed</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/17</td>
<td>3.97</td>
<td>+12</td>
</tr>
<tr>
<td>9/17 and 10/1</td>
<td>3.26</td>
<td>-8</td>
</tr>
<tr>
<td>10/1</td>
<td>3.44</td>
<td>-3</td>
</tr>
<tr>
<td>10/1 and 10/15</td>
<td>2.96</td>
<td>-16</td>
</tr>
<tr>
<td>10/15</td>
<td>2.91</td>
<td>-18</td>
</tr>
<tr>
<td>10/29 and 10/15</td>
<td>1.48</td>
<td>-58</td>
</tr>
<tr>
<td>10/29</td>
<td>2.12</td>
<td>-40</td>
</tr>
<tr>
<td>11/12 and 10/29</td>
<td>1.54</td>
<td>-56</td>
</tr>
<tr>
<td>Control</td>
<td>3.54</td>
<td>-</td>
</tr>
</tbody>
</table>

From the Table it is clear that missing irrigations during the fruit formation stage decreased the productivity greatly (40 – 50%) while missing irrigations during bud formation had a less effect (3 – 8%).

b. **Excess water effect on ground nut:**

The addition of excess water proved its effect on productivity and loss of great quantity of irrigation water in the cotton crop the variety Akala and ground nut led to increase the production cost in addition to the consumption of additional irrigation water which can be used in irrigating additional areas from the same crop or producing another crop (Table 5.2)
Table 5.2 Effect of continued irrigation after mid October on Ground nut productivity

<table>
<thead>
<tr>
<th>Date of continued irrigation after mid October</th>
<th>Productivity of extraction kg/fed</th>
<th>Productivity of dig kg/fed</th>
<th>Loss percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First October</td>
<td>1434</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>Mid October</td>
<td>1866</td>
<td>186</td>
<td>9</td>
</tr>
<tr>
<td>First November</td>
<td>1612</td>
<td>490</td>
<td>23</td>
</tr>
<tr>
<td>Mid November</td>
<td>1416</td>
<td>718</td>
<td>34</td>
</tr>
<tr>
<td>First December</td>
<td>1064</td>
<td>1046</td>
<td>50</td>
</tr>
<tr>
<td>Mid December</td>
<td>818</td>
<td>1202</td>
<td>60</td>
</tr>
</tbody>
</table>

Source: Farah (1999)
c. Irrigation Interval:

When studying the irrigation effect every 7, 12, 14, or 21 days on the productivity of wheat varieties Geeza 155 and Mesektabi (Table 5.3) it can be observed that the productivity declined with increasing the interval between irrigations but there is no significant difference between the grain production between irrigations each 7 and 14 days or between 12 and 14 days in each variety.
Table 5.3 Effect of irrigation interval on the productivity of wheat

<table>
<thead>
<tr>
<th>Variety</th>
<th>Interval between irrigations(days)</th>
<th>Productivity (kg/Fed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Geeza</td>
<td>2643</td>
<td>2900</td>
</tr>
<tr>
<td>Mesektabi</td>
<td>3835</td>
<td>3500</td>
</tr>
<tr>
<td>Mean</td>
<td>3289</td>
<td>3200</td>
</tr>
</tbody>
</table>

Source: Farah (1999)
5.2.1.2 The White Nile water development:

a. The future scope for the Sudan’s water:

The quantity of available water in the future can be predicted from that different sources as can be seen in Table 5.4 and 5.5.

i. Johngoli canal project (A) which includes digging a canal which is 360 km long in Bahr Jabal and Bahr Zaraf and this increases the Sudan water resources with about 2 billion cubic meters / year.

ii. Johngoli project (B) which completes the digging to increase the discharge with about 2 million m$^3$/day with dam construction on Elbert lake which yield about 3.5 billion m$^3$/year

iii. Mashar project which collects the water in a major canal from Elbaro River in Khor Mashar and ends in the White Nile at Milliot. This project yields 2 billion m$^3$/year for Egypt and Sudan.

iv. Northern Bahr Elgazal project:
This project aims to dig a canal to collect water from the northern part of the basin and delivers it to the White Nile. This project yields about 3.5 billion m$^3$/year for Egypt and Sudan. (Ganadi, 2006)
## Table 5.4 Expected water from other projects

<table>
<thead>
<tr>
<th>Projects</th>
<th>Quantity of water expected (billion m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johngoli (A)</td>
<td>2.4</td>
</tr>
<tr>
<td>Johngoli (B)</td>
<td>1.8</td>
</tr>
<tr>
<td>Swamp of Mashar Khor</td>
<td>2.2</td>
</tr>
<tr>
<td>Northern Bahar Elgazal</td>
<td>2.2</td>
</tr>
<tr>
<td>Southern Bahar Elgazal</td>
<td>3.5</td>
</tr>
<tr>
<td>Total</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Source: Ganadi (2006)
Table 5.5 Expected upper Nile water projects:

<table>
<thead>
<tr>
<th>Projects</th>
<th>Installation</th>
<th>The available water at Aswan (billion m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project of decreasing loss in Bahar Eljabal swamp and Bahar Elzaraf.</td>
<td>Johngoli (a): Johngoli canal from bahar Eljabal to Malkal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Johngoli (B): sudd of Elbert lake. Extinction of Johngoli canal.</td>
<td>3.80</td>
</tr>
<tr>
<td></td>
<td>The balance of Fectorya lake. The balance of Kuga lake.</td>
<td></td>
</tr>
<tr>
<td>Project of decreasing loss in Khor Mashar swamp and Sobat river</td>
<td>Baor sudd. Bridge of Mashar Khor. canal of Mashar Khor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.00</td>
</tr>
<tr>
<td>Project of decreasing loss in swamp region in Bahr Elgazal</td>
<td>Bhar Elarab canal. Goor river branch. Ugbeiry two rivers dams. Tonga canal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Bahr Eljabal.</td>
<td>7.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>18.00</td>
</tr>
</tbody>
</table>

Source: Ganadi (2006)
This project should be studied seriously for the social and environmental impacts. The cooperation between Sudan and Egypt and the Nile basin countries is a must to implement such project.

5.2.1.3 Cooperation between the Nile Basin countries:

a. Background of the Nile Basin Initiative:

The Nile basin encompasses ten countries: Burundi, Democratic Republic of Congo, Egypt, Eritrea, Kenya, Rwanda, Sudan, Tanzania, and Uganda. In 1997, the Nile countries initiated a dialogue on a long term cooperative framework and in 1999 the Council of Ministers of Water Affairs of the Nile Basin States (Nile-COM) formally launched the Nile Basin Initiative (NBI) an interim financing mechanism for development of regional projects. The NBI is represented by its executive arm, the Nile Secretariat (Nile-SEC) based in Entebbe, Uganda. Nile-COM has approved a basin-wide integrated program to jointly pursue sustainable development and management of the Nile waters for promoting economic growth, eradicating poverty, and reversing environmental degradation. The program is called the Shared Vision Program (SVP) and includes seven projects, namely:

i. Trans-boundary Environmental Action.

ii. Regional Power Trade.

iii. Efficient Water Use for Agricultural Production.


v. Confidence Building and Stakeholder Participation.

vi. Applied Training.

vii. Socio-Economic Development and Benefit Sharing.

In parallel, Nile-COM also approved action-oriented sub-basin programs, namely the Nile Equatorial Lakes Subsidiary Action Program (NELSAP) and the Eastern Nile Subsidiary Action Program (ENSAP). NELSAP
includes Burundi, Democratic Republic of Congo, Kenya, Rwanda, Egypt, Sudan, Tanzania, and Uganda while ENSAP includes Ethiopia, Egypt, and Sudan. Eritrea is participating in ENSAP as an observer. NELSAP and ENSAP are meant to shift focus from planning to action on the ground through investment in actual development projects. Such projects cover irrigation and drainage development, hydropower development and power transfer network and trade, watershed management, sustainable development of lakes and wetland systems, river regulation, flood and drought management, etc. Nile-COM then formed the Nile Equatorial lakes council of Ministers (NELCOM) and the Eastern Nile Council of Ministers (ENCOM) to oversee the activities of NELSAP and ENSAP, respectively. NELCOM and ENCOM are assisted in their activities by teams of technical specialists from the respective member countries. Following the establishment of ENCOM, Ethiopia, Egypt and Sudan have jointly adopted a strategy to develop, utilize, and manage water resources of the Eastern Nile Basin in an integrated, equitable, and sustainable manner. In defining the cooperative development program, the countries identified sixty-four potential regional projects. Out of these seven priorities, known as the integrated Development of the Eastern Nile (IDEN) were selected. These are:

- Ethiopia-Sudan Interconnection Project,
- Eastern Nile Power Trade Investment Program Study
- Eastern Nile Multi-sector Planning Model,
- Baro-Akobo Multipurpose Hydro Power Project,
- Flood Preparedness and Early Warning,
- Irrigation and Drainage Development, and
- Watershed Management.

In order to prepare, monitor, and supervise the implementation of the IDEN, ENCOM established the Eastern Nile Technical Regional Office (ENTRO) in Addis Ababa.

When implement these dams they should be in low evaporation area and this by cooperation between basin countries specially Egypt, Ethiopia. Many common dams between Sudan, Egypt and Ethiopia for useful the flood water in the Blue Nile between this countries in increase the share of water, generation of electric power and increases the irrigation lands also the difference in the loss and evaporation between Dal (suggested dam) in north Sudan and the dams in Ethiopia that Dal dam the evaporation reach $450 \text{ m}^3 \times 1000/\text{year}$ while in Manday (suggested dam) it reached $50 \text{ m}^3 \times 1000/\text{year}$ (Appendix 1).

So the cooperation between these countries is one of the necessities in developing the water resources in river Nile which lead to increase the Nile water by decreasing the water loss in wet land areas and control of flood water.

5.2.1.4 Protection of river Nile water from pollution:

Nile water agreement in 1959 between Sudan and Egypt did not mention or included the protection of river Nile water from pollution although it is one of the main factors which decrease the water quality of this resource.

Pollution can be controlled by:

- Prohibit spillage of industrial waste, sewerage and agricultural drainage in the river.

- Establishing cooperation between the Nile basin countries to protect the river Nile water from pollution.
5.2.2 Non-nilotic water development (seasonal wadis):

Optimal design and hence sustainable development of seasonal streams wadis requires reliable and properly analyzed data. However, long period monitoring for wadi discharge is essential for determination of capacity and cost of hydraulic constructions, other information including, meteorological, topographic, structural and soil test are required for design completion.

The period between (1966-1982) is considered as the most fulfilling where ant-thirst campaign was launched under the umbrella of the Rural Water Development Corporation and the Rural Water Corporation of the Ministry of Agriculture. It is agreed that the first attempt for proper discharge measurement was made in 1959. The total discharge estimated for 120 major wadis is 7.2 milliard, 2.5 milliard can be harvested, 2.5 milliard replenish the groundwater basins and the remainder is harvested and a big portion is considered as waste.

Despite the good chemical quality of the wadis water, pollution, sedimentation, and the geomorphologic changes resulting from the continuing droughts threaten both the quality and quantity of the seasonal wadis water. To avoid negative environmental impacts, socioeconomic study is a prerequisite for the assessment of the environment situation down and upstream prior to any development. Due to the topographic nature and the wadi diversity of the climatic zone (annual rainfall range is from 10 to 1000 mm), seasonal wadis are considered as one of the significant water resources in Sudan especially in the following areas:

- Of Basement Complex Formation.
- Of groundwater Salinity Zones.
- Remote from the Nile system.
The diversion and utilization of surface water flows for both drinking and growing crops is not new and the technique is widely practiced in the Sudan. A good example of the technique can be seen in North Kordofan, Blue Nile states where big towns and villages depend on harvested surface water in large Hafirs and reservoirs as well as traditional farmers who cultivate large areas using small bounded basins with considerable success.

Water harvesting can take many forms including the following:

- Hafirs (excavated reservoirs).
- Contour Bunds,
- Rill Bunds,
- Micro Catchment’s Basins,
- Diversion and Groundwater Recharge Dykes (groundwater recharge from surface water about 2.5 milliard)
- Impounding dams (Earth, Masonry or Concrete).

Modern and advanced techniques in water harvesting are concerned mainly with applying the method in a more controlled and rational manner, so much can be learnt from the study of the traditional method. Maximum use must be made of the skills and enthusiasms of the beneficiaries who in some form or the other are already practicing the technique.

5.2.2.1 Water harvesting from seasonal streams (wadis):

The harvesting of water became one of the necessities in the recent time which can lead to the increase of water resources and its use in agriculture, for the human being and animals. The construction of small dams on these streams can serve the purpose.
a. Water harvesting:

Rain water harvesting can be defined as the process of collecting water from areas that have been treated to increase run off and snow melt. (Saeed et al., 2003).

Most of the Sudan is characterized by arid and semi arid climate where average annual rainfall vastly exceeds the stream flow. Some of this water is transpired by useful vegetation or percolates into under ground aquifers, but most of it soaks into dry soil and then evaporates directly from the soil or is used by low value vegetation. A considerable amount of the rainfall water constitutes the stream flow (2%-8%). This rainfall runoff coefficient tends to decline in permeable soils and increases in clayey soils. Stream flows in seasonal wadis make them with the most potential for developing new water supplies by means of water harvesting.

The principle of rainfall harvesting can be used for livestock and human use as well as for improving crop and rangeland productivity and for developing farming in an area where it is not naturally feasible. In this case run off of a large area is collected and concentrated in a small area where water is stored or spread on the soil. As a result, soil moisture in the small area for plant growth and development is increased considerably above the amount which would be available from rainfall alone.

Runoff agriculture has particular promise in marginal areas as it lowers the risk of crop failure. There are certain important steps to develop a certain site through application of a certain water harvesting method for particular schemes whether it is water supply for drinking purpose or agricultural purpose.

These steps are:
1. Site selection: From engineering point of view site selection is one that obtains the maximum benefits from the minimum resources. For water harvesting schemes the best sites to achieve this are the area where there are:

- Adequate water,
- Sufficient command,
- Available construction materials,
- Suitable topography and geology.

However, no site is likely to be perfect; a compromise usually should be made in choosing a site and constructing the works for reasonable compliance with all of items listed above. Acceptable location of hydrometric stations can be achieved through interpretation of aerial photos and satellite mapping. Field trips are essential for check.

2. Hydrology: A sound understanding of the hydrologic process is needed to ensure proper use and transformation of data into hydrologic information i.e. Rainfall and evaporation, transpiration, Runoff etc.....

Here comes the importance of the hydrometric stations network as well as rainfall and meteorological stations to collect data on temperature, wind, humidity etc ... .

To obtain a proper understanding of the hydrology consultation or remote sensing data is very important. This includes aerial photos, satellite mappings aided by filed work to solve the disputes raised in the interpretation phase.

Water demand has to be determined very well, i.e. how much water is needed and what the probable resource.
3. Soil Investigation: there is a minimum level of soil testing required to design and implement a water harvesting scheme successfully and this includes the following:

- Particle size analysis,
- Moisture content,
- Dry and bulk densities,
- Atterberg limits,
- Infiltration rate and hydraulic conductivity.

The best soil is of low to very low permeability. Although the geophysical approach is the most appropriate, mainly Electro- Magnetic EM for investigation of both the subsurface soil and its structure, soil testing pits through manual digging and auguring are the mainly used techniques.

4. Topographical Survey: Topographical survey is vital to any type of water harvesting scheme. It is used to determine and obtain the following:

- Configuration of the catchments,
- Characteristics of the wadis i.e. wetted perimeter, hydraulic radius, wetted cross-sectional area and the gradient of the flow.
- Storage capacity of the structures and that can be obtained through making a suitable contour map with suitable interval.
- Determination of fill and cut areas.
- Determination of the slopes of the whole watershed to determine the time of concentration at which, the whole drainage systems contribute at the point of interest in the wadi.
- To facilitate comparison between the hydrometric data and the estimated ones.
- To establish a reference data, map or bench mark to facilitate supervision, monitoring and evaluation of the project.

5. Socioeconomic Studies: the government policy is of decentralization and privatization of water sector activities. The comprehensive National Strategy (1992-2002) calls for community’s involvement in water projects development through self-help policy. Therefore, a comprehensive study has to be made to explore and find out evidence, initiatives and enthusiasm to contribution of the communities in various scheme activities starting from planning through implementation to the monitoring and the evaluation processes.

Also the study is required to consider the major effects on the population whatever it is positive or negative.

d. Environmental Impact Assessment: Environmental Impact Assessment (EIA) is very important in order to measure the positive and negative impact of the project. The following can be considered when carrying out the assessment:

- Purpose and physical characteristics of the project.
- Land use requirements and other physical features.
- Operational features of the project.

Main site alternatives and water harvesting type considered and reasons for final choice (Abdelgadir, 20003).

In Sudan there are some streams which need development to be used in agriculture and domestic uses such as Shalloap delta in north east Kassala which can save about 16.6 mcm per year, Mosran wadi in Albotana area (west New Halfa) which can save about 10.5 mcm per year, sudd Alsisban in wadi Kagara south Kordofan which can save about 24 mcm per year, wadi Shalingo west Kordofan can save 63.7 mcm per year, sudd Jerroia south
Kordofan can save 1.2 mcm per year, Hallofe wadi north Darfor can save about 0.5 mcm per year and Wdaa wadi north Darfor can save about 0.08 mcm per year (Abdalla, 2007).

5.2.3 Rainfall water management:

5.2.3.1 Rainfed cultivation:
The rainfed cultivation occupies about 25 million Feddans and plays a very important role in the national economics where it contributes with a big share in food security of the country which may reach 90%. About 66% of the population is involved in the activities of this sector. The rainfed cultivation is divided in two major parts, the mechanized agriculture in an area of about 17 million Feddans and the traditional sector. This cultivation is featured by low productivity for many factors. The most important factors are the great variation in the rain in quality and quantity, low land fertilely and the effect of insects, grasses and diseases – and also the lack of financing. Farmers don’t follow the recommended cultivation operations. The rain water quantity in Sudan is about 1000 bcm per year but with very high seasonal variability. This leads to decrease the productivity of the unit of water. The research which was conducted in the rainfed cultivation in Sudan was little but the results obtained were encouraging.

5.2.3.2 Rain water management – The rationale:
A broad approach to water productivity in land management that covers both irrigated and rain fed agricultural has implications on water resource management. Conventionally, a focus on global, regional and national freshwater resources and a withdrawal has been considered and also the accessible surface and sub-surface water in the hydrological cycle (Fox et al., 2003).
5.2.3.3 Upgrading rainfed agriculture – challenges and opportunities:

**a. Hydro climatic challenges:**

Water related problems in rain fed agriculture in water scarcity prone tropics are often related to high intensity and large spatial and temporal variability of rainfall, rather than low cumulative volumes of rainfall. Rainfall is highly erratic, and rain often falls as convective storms, with high rainfall intensity and extreme spatial and temporal variability. Coefficient of variation ranges from 20-40%, increasing with decreasing seasonal rainfall averages the overall result of unpredictable spatial and temporal rainfall pattern is a very high risk from meteorological droughts and intra-seasonal dry spells. The annual (seasonal) variation of rainfall can typically range from low of 1/3 of the large term average to a high of approximately double the average; meaning that a high rainfall year can have some 6 times higher rainfall than a dry year. Generally, the hydro-climatic focus in semi-arid and dry sub-humid tropics is on occurrence of meteorological drought. Statistically for semi-arid regions total crop failures caused by meteorological drought occur in the order of once every 10 years (Stewart, 1988). Research from several semi-arid tropical regions show that the occurrence of dry spells, short period of 2-4 weeks with no rainfall, exceeds the occurrence of droughts. Stewart (1988) stated that in East Africa, severe crop reduction caused by a dry spell occurs 1-2 out of five year, showed that the frequent occurrence of seasonal dry spell in the range of 10-5 days were independent of long-term seasonal averages ranging from 200 to 1200 mm in West Africa. Mitigating dry spells is a key to improve water productivity in rainfed agriculture in semi-arid and dry sub humid tropical environment. There are three major avenues to achieve this:
- Maximize plant water availability (maximize infiltration of rainfall, minimize unproductive water losses (evaporation), increase soil water holding capacity, and maximize root depth).
- Maximize plant water uptake capacity (timeliness) of operations, crop management and soil fertility management).

Bridge crop water deficits during dry spells through supplemental irrigation. (Fox et al., 2003)

b. Hydro climatic opportunities:

The on-farm water balance is and entry point to the analysis of the opportunities available to improve water productivity. Fig 5.1 gives a synthesized overview of the partitioning of rainfall in semi-arid rain fed agriculture, based on research experiences in Sub Saharan Africa.
Fig 5.1 General overview of rainfall partitioning in farming system in the semi-arid tropics of Sub-Saharan Africa.

5.2.3.4 Rain water management:

a. Water harvesting for micro-irrigation:
For poor small-holdings, farmers in water scarce areas even small volumes of stored water for supplemental irrigation can significantly improve household economy. In the Gansu Province in China small 10-60 m³ (on average 30 m³) sub-surface storage tanks are promoted at large scale. These tanks collect surface runoff from small, often treated catchments (e.g., with asphalt or concrete).
Research using these sub-surface tanks for supplementary irrigation of wheat in several countries in Ganus province (Fox et al., 2003) indicates a 20% increase in water use efficiency.

b. The supplemental irrigation:

The research in this field began in the first 1980s in Kenana research station, in Abu Na’ama and in Elobied station in Abu Habil project with the addition of organic fertilizers. Bridging dry spells through supplemental irrigation of rainfed crops can be an interesting option to increase water productivity (SIWI, 2001).

c. Conservation tillage:

There is ample research indicating that the conventional farming systems in the tropics, based on soil inversion using plough and hoe, contribute to soil erosion and soil desiccation. Plough pans impede soil infiltration and root penetration, and frequent soil inversion results in oxidation of organic matter and soil erosion by wind and rain (Fox et al., 2003).

Conservation tillage (CT) covers the spectrum of non-inversion practices from zero-tillage to reduced tillage, which aim at maximizing soil infiltration and soil productivity, and minimizing water losses while conserving energy and labour. Even though conservation tillage is not a new phenomenon, the relatively recent successes, e.g. in Brazil, has inspired research and development efforts in Sub-Saharan Africa and Asia. Examples of successful CT system, where crop yield has been significantly increased, soil erosion reduced and conservation of water improved, can be found in several countries in Sub-Saharan Africa, e.g., Ghana, Nigeria, Zimbabwe. However, these successes are mostly confined to commercial farmers.
Conservation tillage has several attractive water productivity attributes. Traditionally, conservation in agriculture has focused on soil conservation (even though labeled soil and water conservation), with the aim of reducing soil erosion.

Table 5.6 Various conservation tillage practices


<table>
<thead>
<tr>
<th>Treatment</th>
<th>RUE [kg mm(^{-1}) ha(^{-1})]</th>
<th>SD</th>
<th>Control no Fertiliser</th>
<th>Control with Fertiliser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripper</td>
<td>10.1</td>
<td>4.9</td>
<td>*** 2.8</td>
<td>* 1.4</td>
</tr>
<tr>
<td>Ripper + CC</td>
<td>10.6</td>
<td>5.8</td>
<td>*** 2.9</td>
<td>** 1.5</td>
</tr>
<tr>
<td>Ripper - FERT</td>
<td>8.4</td>
<td>3.7</td>
<td>*** 2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Pitting</td>
<td>8.2</td>
<td>4.1</td>
<td>*** 2.3</td>
<td>* 1.2</td>
</tr>
<tr>
<td>C+FERT</td>
<td>7.0</td>
<td>4.4</td>
<td>*** 2.0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.8</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cc: Cover crop
C: Conventional mouldboard plough
RuE: Rain use efficiency
Ripper: Magoye ripper

Rain use efficiencies increased when shifting from a mould board plough based system (c: control) to various conservation tillage practices (Table 5.6). The data originates from two years (long rains 1999 and 2000) with 6-8 farmers and two replicates farm. The improved water use efficiencies are explained primarily by improved timing of planting, root penetration and soil infiltration (Fox \textit{et al}., 2003).

The rain water harvesting techniques with the addition of organic fertilizers led to a great increase in productivity (Farah, 1993).

Following the supplementary irrigation, conservation tillage, water harvesting for micro irrigation, all these technique lead to increase the
efficiency of using rain water in rainfed sector to sustain this effect the following point are important:
- Continue water harvesting with adoption of the most effective technique.
- Supplementary irrigation technique application where suitable.
- Training the farmers in the rain fed sector on the new technologies which lead to increase the productivity of water.

5.2.4 The groundwater development and management:
The management of these resources requires the following:
a. More studies to determine the water quantities in the basins and water quality by:
   i. Making integrated maps explaining the groundwater places.
   ii. Determine the quantity required for domestic, industry and agricultural uses.
   iii. Protect this resource from pollution.
   iv. Cooperation between the countries which share with Sudan any basin for development of that basin.
   v. Maximize the hydraulic efficiency and economic productivity of the basin.
b. Additional management action for sustainable groundwater resource:
   To secure more effective water management and planning to achieve a level of sustainable utilization the following suggestions should be observed:
   i. Good supervision, management and monitoring of this resource.
   ii. Sound research of water supplies and storage volumes.
   iii. Suggest the required organization needed for water resource protection.
   iv. Develop mechanisms, framework and implementation of strategies for private sector involvement, operation and maintenance of groundwater facilities.
v. Control leakage and minimize water loss from water supply networks.

c. Artificial recharge of groundwater:

More studies and research should be applied in the different regions for artificial recharge.

5.2.4.1 Artificial recharge:

Artificial recharge has been defined by Todd (1959) as “the practice of increasing, by artificial means, the amount of water that enters a ground water reservoir.” Such a practice is, recently, increasingly emerging as a powerful tool in water resource management, at different levels of time and space. In several situations, however, the vast exploitation of particular water resources by agricultural, industrial or municipal demands had led to a mandatory adoption of that technique. For example it has recently been published by Osterhoudt (1972) that irrigation, in Curry and Roosevelt Counties of New Mexico, U.S.A., would be reduced or even eliminated by the year 2020, due to the depleting ground water resources. Similar frightening warnings were reported from many other locations in the western and southwestern United States, especially those from Texas’s irrigation industry where artificial ground water recharge was prescribed as a feasible solution. The feasibility of artificial recharge as a water resources technique allowed its use in situations where there are qualities rather than quantity constrains on these resources. A typical example of that use has been reported by Guymon (1972) from Alaska, U.S.A., where abundant quantity of water resource exists.

5.2.4.2 Purpose of artificial recharge:

The one diverse purposes for which artificial recharge is practiced, or recommended for practice, not only in different countries of the world but also between different projects within the same country. Basic of these
purposes are: Storage of fresh water, raising declining water table, water reclamation, flood control, water quality preservation or improvement, building barriers against saline and low quality water intrusion, subsidence abatement, raising artesian pressure, disposal of cooling water, disposal of wastewater and management of water resources.

1. Storage of fresh water:

The availability of the unsaturated zone as a potential reservoir for subsurface storage has encouraged the recent, wide, utilization of this technique in many parts of the world. Subsurface storage could have many advantages over surface storage. Among these advantages are the following:

a- Many large capacity sites are available within the unsaturated zone.

b- Of slight or no evaporation losses.

c- Require little land area at the surface.

d- No loss of storage capacity by sedimentation.

e- High biological purity.

f- Less danger due to contamination.

g- Reduction of temperature fluctuation.

h- Light is excluded.

i- Reservoir servers as conveyance system.

The above advantages have made subsurface storage an economically competitive technique when compared to surface storages. From a model study, Mawer and O’Kane (1970) indicated that while artificial recharge
would be more favorable over surface storage at high degree of regulation and on rivers of high persistence in their flow characteristics, yet a combined system of surface storage of upstream of artificial recharge could result in significantly lower costs than those associated with either of these single systems. A very recent development in this respect is the reported successful storage of fresh water in saline aquifer. Such utilization has been investigated, among others, by Kimber et al., (1973) who described it as a feasible storage technique. This purpose of artificial recharge has been widely used in many places of the world. Its utilization in Sudan can be very successful in the central, rain fed cultivation and grazing livestock region of the country. Furthermore the storage of fresh water in saline aquifers can be utilized in Gadarif dura cultivation area to solve the shortage in domestic water needs at the time of harvesting.

2. Raising declining water table:

Lowering of ground water levels occurred in many aquifers where pumping exceeded the natural recharge. By artificially recharging such aquifers deepening of wells could be avoided, pumping costs would be reduced, and threats to water quality especially for aquifers near coasts or polluted rivers could be eliminated, in addition to other benefits. Typical examples in this respect are the alarming depletion in the Ogallala aquifer in the high plains of Texas and New Mexico, U.S.A., where multi-billion dollars agricultural industry was threatened by complete elimination. By artificially recharging Playa-Lake-water to that aquifer, the present powerful economy of that area seemed to survive future decline. Examples from the Sudan, where the technique may be used, include the declining aquifers at Kassala, Khartoum, Niyala, and Port-Sudan areas.
3. Water reclamation:

Artificial recharge is either utilized as recommended for application in many parts of the world for waste water purposes including domestic water supply. Reclamation, however, may include in this sense, the utilization of storm runoff, highway storm drainage, or any other sources of surface water which, otherwise, would have been lost to evaporation or other forms of losses. This technique can be used literally in all parts of the Sudan, especially in areas with limited water resources.

4. Flood control:

Artificial recharge has been reported by Jones (1919) as a measure of flood control in California, U.S.A. Similar adoption of this technique can be investigated for many areas in the Sudan, especially spreading of excess Gash river water to protect Kassala town.

5. Water quality preservation or improvement:

Aerobic recharging of degradable water through permeable soil layers to the water tables is found to be effective in removing biodegradable material, pathogenic organisms, and certain chemical components. Land application is also capable of efficient removal of suspended soil particles from turbid water. Unfortunately, such removal is frequently linked with the troublesome clogging phenomenon. Quality improvement through artificial recharge is widely used in Germany, Netherlands, Switzerland, Sweden and other places of the world. Artificial recharge can be used for preserving certain qualities of the recharged water. For example water is recharged in Alaska, U.S.A., for temperature preservation through winter. The above aspects can be investigated for several localities in the Sudan.
6. Building barriers against saline and low quality water intrusion:

Artificial recharge is used as a technique against seawater intrusion in many coastal parts of the world. Such a barrier is formed by spreading or injection of fresh water. A recent development in this technique includes its utilization for protecting fresh water aquifers from polluted rivers or salinated aquifers. Engineering and operational aspects related to this technique are highly developed in the United States of America through California’s, New York’s and Florida’s, experiences. Its application in the Sudan has been investigated for Port-Sudan.

7. Management of water resources:

Artificial recharge has also been reported by Scalapine (1949) as a means of raising artesian pressure in Texas, U.S.A., by Garza (1977) for subsidence abatement at Nasa- Johnson Space Center in U.S.A., and for disposal of cooling water and wastewater in many places in the world. The variety provided by all of the above reviewed purposes has strongly suggested the adoption of artificial recharge as an effective water resources management technique. The success of such adoption requires the integration of the available knowledge in many disciplines (chemistry, biology, geology, economy, low, sociology, health, politics, etc.) with that of engineering aspects. An example of such application was reported by Brown et al., (1978) from the high plains of Texas and New Mexico, U.S.A. similar application can be investigated for many areas in the Sudan.

5.2.4.3 Methods of artificial recharge:

Methods for artificial replenishment of groundwater may be classified into the following three main categories;

a- direct,
b- indirect, and

c- incidental methods

**a. Direct methods:**
Direct methods can further be divided into surface (spreading, over irrigation, ponds, etc.) and subsurface (wells, shafts, pits, etc.). In surface method, recharge is accomplished by applying the water on the permeable ground surface where it infiltrates through the unsaturated zone to reach slowly the underground water table. Because of their economy and easiness in operation, the surface techniques, particularly spreading methods, are the most widely used for artificial recharge. Spreading recharge is normally achieved through basins, furrows or ditches, or regulated stream channels. On the other hand irrigation recharge is achieved through excessive application of water in irrigation areas, while pond recharge is accomplished through replenishment from a water source of relatively large surface area.

Subsurface techniques are practiced in locations where there are layers of such low vertical permeability between the ground surface and the unsaturated upper level of the recharge aquifer that infiltration becomes not feasible. Generally, these techniques are utilized only if surface methods can not be satisfied technically and economically. Inspite of the uncontestable superiority of surface methods, subsurface methods have the following advantages:

i. They occupy smaller areas.

ii. They utilize better quality recharge water.

iii. They are capable of recharging aquifers that don’t extend to the ground surface.
iv. They can be designed so as to avoid undesirable mixing between the recharged and pumped water.

b. **Indirect methods:**

Indirect methods of recharge are meant to include types of recharge that are included by pumping from an aquifer hydraulically connected to a surface reservoir, a river, a canal, or another aquifer. Although this technique has limited applications if compared to the direct methods, its usefulness in certain localities is beyond comparison.

c. **Incidental recharge:**

Incidental recharge includes non-deliberate replenishment from irrigation systems, leaking domestic and industrial systems, and disposed industrial and domestic wastewaters. In spite of its significant contribution to the groundwater, this last method was the least investigated technique. For example it has been published by Schmidt (1978) that from the estimated $29.03 \times 10^9$ m$^3$ of the United States municipalities waste water in 1970, only about $510 \times 10^6$ m$^3$ were reported to have been reused by formal methods in 1971. The rest might have recharged the groundwater reservoir by an informal way or another.

**5.2.4.4 Selection of method:**

Each of the above, broadly reviewed, methods has its advantages and disadvantages. However it can be stated that the best artificial recharge method is the one that can maintain a high infiltration rate, increase the wetted areas, and lengthen the period of infiltration at an economical level and with sustained desirable quality of water. With this definition in mind, it will be impossible to specify a particular method as being the best for all
localities in the Sudan. However the best method at a particular location, in the Sudan, will require more detailed investigation on the quantity and quality of the available source of recharged water, and the overall characteristics of the aquifer and the overlying formation. (Salih, 1987)
CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions:
From this study the following conclusions can be drawn:
1. The conventional water resources of Sudan need to be accurately assessed to make plans for sustainable development and management.
2. Sudan needs to cooperate with the different Nile basin countries in the future to develop the basin.
3. The seasonal streams represent a very important recourse in Sudan if it is well developed.
4. Some techniques can be used in the rainfed sector which increase the productivity of crops by using rain water harvesting and conservation tillage.
5. It is essential that the groundwater resources be monitored and managed by protection against pollution and also developed by using artificial recharge.
6. Introduction of modern Irrigation system, increasing the efficiency of the existing surface irrigation systems and adoption of supplemental irrigation in certain areas.
6.2 Recommendations:

From the discussion and conclusions drawn from this study, the following recommendations can be made:

1. Future research should focus on water resources assessment and management.

2. Development of data base and monitory station of rain and stream for efficient water harvesting design.

3. Adoption of water harvesting techniques in the rainfed agriculture.

4. Adoption of artificial ground recharges techniques where applicable.

5. Development of the seasonal wadis and streams.

6. Adoption of sound irrigation management practices.

7. Introduction of modern irrigation systems where appropriate.
REFERENCES


APPENDICES

Appendix 1

Blue Nile (Abbay River) Basin:
- Mandaya project
- Border Project
- Dal Project

Hydrology – Catchment’s Areas and Flows:

<table>
<thead>
<tr>
<th>Site</th>
<th>Catchment Area (km²)</th>
<th>Mean Annual Flow (Natural) (m³/s)</th>
<th>Mean Annual Flow (with Beles Diversion) (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kessie</td>
<td>65,784</td>
<td>517</td>
<td>440</td>
</tr>
<tr>
<td>Karadobi</td>
<td>82,300</td>
<td>649</td>
<td>572</td>
</tr>
<tr>
<td>Mandaya</td>
<td>128,729</td>
<td>1091</td>
<td>1014</td>
</tr>
<tr>
<td>Border</td>
<td>176,918</td>
<td>1547</td>
<td>1547</td>
</tr>
<tr>
<td>El Deim</td>
<td></td>
<td>1547</td>
<td>1547</td>
</tr>
<tr>
<td>Dal</td>
<td></td>
<td>2055</td>
<td>2055</td>
</tr>
</tbody>
</table>

Comparison of Reservoirs:

<table>
<thead>
<tr>
<th>Item</th>
<th>Karadobi</th>
<th>Beko Abo</th>
<th>Mabil</th>
<th>Mandaya (USBR)</th>
<th>Mandaya FSL 800</th>
<th>Border</th>
<th>Low Dal</th>
<th>Aswan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Supply Level (m)</td>
<td>1146</td>
<td>915</td>
<td>906</td>
<td>741</td>
<td>800</td>
<td>580</td>
<td>201</td>
<td>175*</td>
</tr>
<tr>
<td>Min. Operating Level (m)</td>
<td>1100</td>
<td>900</td>
<td>837.8</td>
<td>724.8</td>
<td>760</td>
<td>560</td>
<td>201</td>
<td>147</td>
</tr>
<tr>
<td>Tailwater Level (m)</td>
<td>915</td>
<td>800</td>
<td>762</td>
<td>610</td>
<td>610</td>
<td>495</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>Gross Storage (m³ x 10⁹)</td>
<td>40.2</td>
<td>13.6</td>
<td>15.9</td>
<td>49.2</td>
<td>13.3</td>
<td>2.4</td>
<td>121.3*</td>
<td></td>
</tr>
<tr>
<td>Gross Storage (% x MAR)</td>
<td>223</td>
<td>75</td>
<td>50</td>
<td>154</td>
<td>27</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live Storage (m³ x 10⁹)</td>
<td>17.3</td>
<td>10.4</td>
<td>4.8</td>
<td>24.6</td>
<td>7.9</td>
<td>0.3</td>
<td>90.7*</td>
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<tr>
<td>Reservoir Area (km²)</td>
<td>460</td>
<td>244</td>
<td>334</td>
<td>736</td>
<td>574</td>
<td>300</td>
<td>5168</td>
<td></td>
</tr>
</tbody>
</table>

* Active storage, excludes flood storage range El. 175 - El. 183m

Comparison of Mandaya with Mabil:
### Project FSL

<table>
<thead>
<tr>
<th>Project</th>
<th>FSL (m)</th>
<th>MOL (m)</th>
<th>MW</th>
<th>Firm energy GWh/yr</th>
<th>Average energy GWh/yr</th>
<th>Gross storage m³ x 10⁹</th>
<th>Live storage m³ x 10⁹</th>
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<tr>
<td>USBR (1964)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Mandaya USBR</td>
<td>741</td>
<td>724.8</td>
<td>1620</td>
<td>7500</td>
<td>16.2</td>
<td>5.6</td>
<td></td>
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<tr>
<td>Mabil USBR</td>
<td>906</td>
<td>837.8</td>
<td>1200</td>
<td>5314</td>
<td>13.25</td>
<td>10</td>
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<tr>
<td>Total (1953-63)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted Total (1953-2003)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>RAPSO</td>
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<tr>
<td>Mandaya USBR</td>
<td>741</td>
<td>724.8</td>
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<td>3559</td>
<td>16.2</td>
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</tr>
<tr>
<td>Mandaya 800</td>
<td>800</td>
<td>760</td>
<td>2000</td>
<td>11194</td>
<td>49.2</td>
<td>24.6</td>
<td></td>
</tr>
<tr>
<td>Mandaya 860</td>
<td>860</td>
<td>820</td>
<td>2400</td>
<td>15676</td>
<td>106.7</td>
<td>41.4</td>
<td></td>
</tr>
</tbody>
</table>

### Sediment Data for Abay at Kessie:

\[
y = 858.73x^{0.2035} \quad R^2 = 0.0625
\]

\[
y = 1.1149x^{1.2825} \quad R^2 = 0.8341
\]

\[
y = 154.53x^{0.428} \quad R^2 = 0.3043
\]

**Sediment Discharge Estimate for Abay at Mandaya:**

---

78
<table>
<thead>
<tr>
<th>Location</th>
<th>Catchment Area (km²)</th>
<th>Specific Suspended Sediment Discharge (t/km²/yr)</th>
<th>Average Sediment Load* (million tonnes / yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kessie*</td>
<td>68,074</td>
<td>2,791</td>
<td>220</td>
</tr>
<tr>
<td>Incremental catchment area Kessie to Mandaya</td>
<td>60,655</td>
<td>900</td>
<td>65</td>
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<tr>
<td>Mandaya</td>
<td>128,729</td>
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<td>285</td>
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</table>

*based on data for Year 2004 including bedload

Mandaya Project:

Mandaya Site:

Selection of Mandaya Full Supply Level:
### Mandaya Options

<table>
<thead>
<tr>
<th>FSL (m)</th>
<th>Area (km²)</th>
<th>Gross Storage (m³ x 10⁹)</th>
<th>Live Storage (m³ x 10⁹)</th>
<th>Live Storage % of MAF</th>
<th>Regulated Flow %</th>
<th>Spillage %</th>
<th>Installed Capacity (MW)</th>
<th>Firm Energy (GWh/yr)</th>
<th>Firm Energy %</th>
<th>Average Energy (GWh/yr)</th>
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</thead>
<tbody>
<tr>
<td>741</td>
<td>334</td>
<td>16.2</td>
<td>5.6</td>
<td>17.5</td>
<td>75.9</td>
<td>24.1</td>
<td>1600</td>
<td>3,559</td>
<td>52%</td>
<td>6,799</td>
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<tr>
<td>800</td>
<td>736</td>
<td>49.2</td>
<td>24.6</td>
<td>76.9</td>
<td>94.4</td>
<td>5.6</td>
<td>2000</td>
<td>11,194</td>
<td>92%</td>
<td>12,119</td>
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<tr>
<td>860</td>
<td>1219</td>
<td>106.7</td>
<td>41.4</td>
<td>130</td>
<td>95.5</td>
<td>4.5</td>
<td>2400</td>
<td>15,676</td>
<td>95%</td>
<td>16,467</td>
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</table>

**Reservoir Operation – Mandaya (FSL 800):**

RAPSO Ver 2.55 on 2/1/2007; Scott Wilson for ENTRO
Mandaya with FSL 800m and 2000 MW

Inflow = 1129.9 & Discharge = 998.7 m³/s
Summary of Energy Outputs from RAPSO:

<table>
<thead>
<tr>
<th>Option</th>
<th>Installed Capacity (MW)</th>
<th>Energy Output (GWh/year)</th>
<th>Base Firm</th>
<th>Average Firm</th>
<th>With Mandaya Firm</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karadobi</td>
<td>1,600</td>
<td>8,276</td>
<td>8,802</td>
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<tr>
<td>Mandaya FSL 800</td>
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<td></td>
<td></td>
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<td>Border</td>
<td>1,200</td>
<td>3,966</td>
<td>6,011</td>
<td>7,429</td>
<td>8,114</td>
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<tr>
<td>Low Dal</td>
<td>340</td>
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<td></td>
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<td>2,187</td>
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<tr>
<td>Uplift at Existing Power Stations</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,211</td>
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<tr>
<td>Uplift at Existing Power Stations</td>
<td>135*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,657</td>
</tr>
</tbody>
</table>

* Additional plant at Roseires

Multi-purpose Benefits of Mandaya and Border:

- Enhanced irrigation potential in Sudan
- Reduced sediment in Roseires reservoir
- Reduced sediment in irrigation systems in Sudan
- Flood alleviation at towns along Blue Nile and Nile including Khartoum

Multi-purpose Benefits of Mandaya - Flood Alleviation at Khartoum:

- Typical dry season flows of Blue Nile at Khartoum at present 100 m³/s – 300 m³/s

Multi-purpose Benefits of Mandaya - Irrigation Potential:

- Typical minimum dry season regulated flow of Blue Nile at Khartoum with Mandaya 600 m³/s – 650 m³/s
## Summary of Energy Outputs from RAPSO:

<table>
<thead>
<tr>
<th>Option</th>
<th>Installed Capacity (MW)</th>
<th>Energy Output (GWh/year)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Base</td>
<td>Firm</td>
<td>Average</td>
</tr>
<tr>
<td>Karadobi</td>
<td>1,600</td>
<td>8,276</td>
<td>8,802</td>
<td></td>
</tr>
<tr>
<td>Mandaya FSL 800</td>
<td>2,000</td>
<td>11,194</td>
<td>12,119</td>
<td></td>
</tr>
<tr>
<td>Border</td>
<td>1,200</td>
<td>3,966</td>
<td>6,011</td>
<td>7,429</td>
</tr>
<tr>
<td>Low Dal</td>
<td>340</td>
<td>1,944</td>
<td>2,187</td>
<td></td>
</tr>
<tr>
<td>Uplift at Existing Power Stations</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uplift at Existing Power Stations</td>
<td>135*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Additional plant at Roseires

## Multi-purpose Benefits of Mandaya and Border:

- Enhanced irrigation potential in Sudan
- Reduced sediment in Roseires reservoir
- Reduced sediment in irrigation systems in Sudan
- Flood alleviation at towns along Blue Nile and Nile including Khartoum
Multi-purpose Benefits of Mandaya - Flood Alleviation at Khartoum:

- Typical dry season flows of Blue Nile at Khartoum at present: 100 m$^3$/s – 300 m$^3$/s
- Typical minimum dry season regulated flow of Blue Nile at Khartoum with Mandaya: 600 m$^3$/s – 650 m$^3$/s
- Uplift in firm flow approx. 400 m$^3$/s over 8 month dry season
- Irrigation potential: 300,000 to 500,000 ha, subject to limit of Sudan share of Nile flow

Location of Project Sites in Sudan:
Dal Site looking upstream:

Conclusions:
• Mandaya and Border projects are highly attractive
• Low energy cost

• Mandaya provides substantial multi-purpose benefits (irrigation, flood alleviation)

• Recommended for development as part of an integrated regional power system

• Dal has higher energy cost, not suitable as a regional project

Future Project Stages:

• Preliminary activities

• Detailed Feasibility studies

• Environmental Sub-studies

• Detailed ESIA

• Tender design and bid documents

• Bidding and award of contracts

• Construction

• Operation and maintenance

• Environmental and social monitoring

Preliminary Activities – Mandaya:

• Access Track for 4WD vehicles

• Install Gauging Station with Cableway, Staff Gauge and Recorder

• River level and flow measurements, sediment sampling
• Topographic mapping 1:1,000 scale, 2 m contour

• Geological investigations (drilling, seismic, insitu testing, lab tests)

• Hydrological studies (floods, sediment)

Project Formulation Studies – Mandaya:

• Legal Arrangements

• Financing

• Trading arrangements

Location of Project Sites in Ethiopia:

Policy, Legal, Administrative Framework Abbay cascade:
There are no environmental policy or legal obstacles

- Ethiopia – Gilgel Gibe good precedent

- World Bank – safeguard policies

- Triggers 4 No. World Bank safeguard policies:
  
  - Environmental Assessment
  
  - Projects on international waterways
  
  - Involuntary resettlement
  
  - Dam safety

- May trigger three more: natural habitat, forests and physical cultural resources

**Conclusions on Impacts:**

1. Power generation and power trading

2. Land loss - biodiversity

3. Land loss – minerals

4. Land loss – socio-economy

5. Land loss – transmission lines

6. Water loss – reservoir evaporation

7. Air Quality – carbon emissions

8. Water Quality

9. Reservoir sedimentation
10. River morphology in Sudan
11. Annual flood – urban flooding in Sudan
12. Annual flood – recession agriculture in Sudan
13. First filling of cascade of dams
14. Regulated flows in Sudan
15. Water supply in Egypt
16. Roads and bridges in Ethiopia and Sudan
17. Dam safety – all countries
18. Institutional strengthening – all countries

Power generation costs and energy sales:
Mandaya 12,100 GWh/year, sales revenue USD 450 million/year
Uplift in Sudan 2,200 GWh/year, sales revenue USD 88 million/year

Land Loss – Resettlement Numbers:
• Karadobi – nil or very few
• Beko Abo – not studied, probably very few
• Mandaya – 600 Resettlement Action Plan
• Border – 14,000 Resettlement Action Plan
• (Dal – 42,000 Resettlement Action Plan)

• Land Loss – Resettlement
• Socio-economic profile –

Ethnic groups: several, including Gumuz
• Religions: Muslim, Christian and traditional
• Low level income
• Limited access to health services
• Low education level and high illiteracy rates
• Food deficiency and malnutrition
• High morbidity and mortality
• Land Loss – Resettlement
• Socio-economic profile

Main crops:
  • sorghum, maize, pulses, oil seed, sesame, vegetables

Livestock:
  • cattle, sheep, goats, poultry, beehives

Shifting agriculture common in BG but not common in Amhara

Education:
  • Primary enrolment rate: better for boys (65%), girls (35%)

Problem: high drop out rate

Public Health:
  • Poor Housing – health issues
  • Burden of diseases – generally preventable
  • Scarcity of health facilities; large distances

Land Loss – Habitat and Biodiversity:
• Abbay cascade reservoirs would occupy about 600 km of 900 km between Lake Tana and Sudan border

• Fortunately …. at this stage, no known threatened or endangered terrestrial or aquatic plant or animal species

• But …. detailed ecological surveys required, over 2 years

• Environmental offset(s) required. Dabus controlled hunting area is suggested as one of these

Water Loss – Reservoir Evaporation:
Air Quality - Carbon Emissions (million tons)

**Mandaya and Border**

During construction 2.3

Decomposition of biomass 3.5

Total 5.8

Equivalent emissions from thermal Plant over 50 years 634 (c. 110 times greater than hydro)

**Water Quality:**

Abbay existing condition – good water quality

Reservoir water quality and releases

- Reservoir water quality modelling is required

- Model will assist determination of how much clearance of woody material is needed

**Reservoir Sedimentation:**

Current sediment transport rates are not known, but believed to be high and increasing
Need for
• much more sediment monitoring
• implementation of Abbay watershed management program
• support from power trade investment program

Trapping of sediment in Abbay cascade dams has benefits for reservoirs in Sudan and Egypt

River Morphology:
Changes in river morphology expected in Sudan
• Egypt’s Aswan experience is important
• Expect to implement some mitigation measures in anticipation and before Abbay cascade developments
• Expect some mitigation measures after Abbay developments
• Required - River morphology study

Multi-purpose Benefits of Mandaya:
• Uplift in energy generation
• Enhanced irrigation potential - 300,000 to 500,000 ha, subject to limit of Sudan share of Nile flow
• Reduction in energy costs for pumping – raised water levels
• Reduced sediment in Roseires and other reservoirs
• Reduced dredging costs at Roseires
• Reduced canal and drainage canal desilting maintenance costs
• Reduced water treatment costs
• Reduction in pump replacement costs
• Flood alleviation at towns along Blue Nile and Main Nile including Khartoum and Dongola

Fisheries
Fisheries development at Abbay cascade reservoirs
Better light penetration, greater primary productivity and improved fisheries at Roseires reservoir – 290 km²
Currently about
• 22 fish species
• 1,200 fishermen
• 550 boats
• 1,500 tons/year (88% of potential)
Areas supported by Annual Flood:

<table>
<thead>
<tr>
<th>Nile reaches Ethiopian Mandaya to Lake Nubia</th>
<th>Agricultural Area ha</th>
<th>Agricultural Area feddan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethiopia Mandaya to Roseires dam</td>
<td>300</td>
<td>700</td>
</tr>
<tr>
<td>Roseires dam to Khartoum</td>
<td>83,800</td>
<td>200,000</td>
</tr>
<tr>
<td><strong>Blue Nile</strong></td>
<td><strong>84,100</strong></td>
<td><strong>200,700</strong></td>
</tr>
<tr>
<td>Khartoum to Merowe dam</td>
<td>169,100</td>
<td>402,000</td>
</tr>
<tr>
<td>Merowe dam to Lake Nubia (Wadi Halfa)</td>
<td>110,900</td>
<td>264,000</td>
</tr>
<tr>
<td><strong>Main Nile</strong></td>
<td><strong>280,000</strong></td>
<td><strong>666,000</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>364,100</strong></td>
<td><strong>866,700</strong></td>
</tr>
</tbody>
</table>

Mitigation for loss of Annual Flood:
Conversion of flood recession agriculture to perennial irrigation – maintaining productivity

- Egypt’s Aswan past experience is very important
- **Required** - Pre-feasibility irrigation study
- **Required** - Feasibility irrigation study
- It will be essential that proposal is culturally acceptable
- Hence, public participation in ESIA studies required alongside thorough engineering and agricultural studies
- Energy for pumping about 0.5% of average annual generation at Mandaya, or about 3% of uplift in Sudan cascade
- **NOTE WELL.** Conversion required before Abbay dams

First filling of Abbay reservoirs (1 of 3)
Blue Nile (Abbay) Optimisation study required

- To quantify impacts and resolve problems for Sudan’s hydropower and irrigation supplies during first filling
- To quantify impacts and resolve problems for High Aswan Dam and Lake Nasser/Nubia

**Major Issues:**

- how to develop say 50 to 100 BCM storage in Ethiopia
- maintain supplies in Sudan and Egypt, and
- compensate for reduced storage and therefore reduced levels at High Aswan Dam

Preparation. Prepare and obtain additional baseline information in advance of formal studies being com