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SCHOOL OF POST GRADUATE STUDIES

Assessment of the Dynamics of Sudd Swamp Hydrology Using Water Balance Techniques

The case study of the Bahr el Jebel basin in south Sudan

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CERTIFICATION

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This thesis is my original work and has not been presented by me or by any other person for a degree award in any university and that all sources of material used in the thesis have been referred to original sources.

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ABSTRACT

Sudd swamp area is the largest wetland in Africa, which is located in the central part of south Sudan. As results of the huge waters losses over Sudd swamp region due to evaporation. Beside reclamation of the land for development and other soci-economic activities, the area has be under raising tension, high conflicts and oppositions between managers and planners of water resources on one side and land users and environmentalists on other on how this swamp can be managed and utilized for the benefits both at locally and regionally.

The objective of this study is to assess the Sudd swamp inundation area, volume and hydrological components controlling the swamp area. The method adopted to quantify the Sudd swamp water dynamics is application of the continuity equation. The monthly water balance of Sudd swamp area is determined from rainfall, evaporation, inflow and outflow of Sudd swamp region. Average rainfall for the area was estimated using Thiessen polygon for stations inside and outside the swamp area. Evaporation was estimated using Cropwat, Hamon and Thronthwaite methods. Inflow and outflow for the swamp area are time series flows measured at two stations.

The potential evaporation has been estimated by the Thronthwaite method for Sudd swamp area at 1706 mm year and the monthly averages range between 89 to 207 mm.

The average monthly inundation area from 1950 to 2009 of the Sudd area has been found range from 14600 to 21500 Million m^2 with mean volume of 249660.2 Million m^3. The study also shows that the effect of climate change and human interference is very high on reduction of the flooding area. The increase of the temperature by three 3 ^{0}C and reducing of rainfall amount over the Sudd swamp area by 10%, 15% and 25% of monthly precipitation amount , are both extreme reducing the swamp inundation area from 69.7 % up to 86.8 %. Also the abstraction or diversion of 50% of the river inflow into Sudd swamp is reducing the swamp total annual area from 212211.19 Million m^2 to 15714.7 Mill m^2, which is a reduction by 92.6 % of the normal flooding areas. The total annually yield of three sub-basins ,Bahr el Jebel , Bahr el Ghazal and Sobat outflows, which is as a total gain of White Nile is 31958.53 MCM/yr.

CHAPTER ONE

1. INTRODUCTION

1.1 Background

The hydrology of lakes and swamps in the Nile basin has been studied from the point of view of at least three interdependent interests (Kebede, 2006). One is related to developing hydrological models for water resources utilization. The second is related to testing the impacts of the natural climate fluctuation such as the ENSO (El Niño Southern Oscillation) or human induced climate changes such as global warming on Lake and swamps Hydrology. The third is related to modeling lake levels or outflows from swamp to use it later to quantitatively interpret historical lake level and swamp area records in terms of past climate variations.

Since the water resources of Nile basin are shared by ten riparian countries, many previous hydrological studies attempt to come up with hydrological models of the Nile from which exploring scenarios can be used as a basis of agreements on water resources sharing. While some countries emphasize that the current models or the existing data can be used as basis of water resources development others emphasize the need of further hydrological studies. Whatever the case may be, the hydrology of the Nile has been reviewed often by many (Shahin, 1988; Sutcliffe and Parks, 1999; and Kebede 2006).

Because of the complexity in the climate and hydrological characteristics of the sub basins of the Nile, improvement in the existing water resources models or the development of new models requires sub basin scale hydrological modeling which can be combined to produce sound models for the Nile basin. The hydrology of many large lakes and swamps of the Nile has been relatively well documented. Examples include Lake Victoria, the Sudd swamp and the Blue Nile basin (Kebede, 2006).

Wetlands are lands that are transitional between terrestrial and aquatic systems where the watertable is usually at or near the surface of the land or the land is covered by shallow water (Cowardin et al 1979, Roggeri 1995). In the context of arid and semi-arid environments, wetlands are transitional areas that are permanently, seasonally or occasionally waterlogged with fresh or saline water, including both natural and man-made areas that support characteristic fauna and flora (Mermet 1986, Dugan 1990).

The swamp area in Southern Sudan is one of the largest wetlands in Africa (Shahin, 2002). The Sudd region has, for long periods of time, been inaccessible due to civil wars in southern Sudan. While studies have been carried out using remote sensing products (Mohamed, 2005), on-ground data have not been available since the old stations, set up by the Egyptian Ministry for Irrigation had been abandoned or destroyed; the last ones is in 1983. The important of the Sudd wetland for the local and regional levels are: fisheries, groundwater recharge, moisture recycling, grazing and biodiversity. Especially the area is the meeting zone of the pastoralists; hence it is under extensive grazing. The swamp of the Sudd is the area with much water of the Nile outflow from Lake Victoria, rainfall over the area and torrents inflow area loss, only about half of the inflow of the Bahr El Jebel reach to the White Nile at Malakal .Because of the channel capacities are less than flood and also the channel bed are above the floodplain, the water spills from the river into the permanent and seasonal swamp and subsequently evaporate, (Sutcliffe, 1974).

The swamp area estimation is so important from hydrological, fishery, agricultural, environmental monitoring and economical point of views. Understanding the dynamic behaviors of the Sudd area throughout the year, besides figuring the link between hydrological regime and the distribution of the vegetation of the flood plain are the key point for any future development projects in the Southern Sudan region, (Shamseddin, 2006).

This research was aimed at far better understanding of the hydrological behaviors of Sudd areas throughout the year or seasons, to estimate the Sudd area through using water balance techniques. Also, the paper aimed to re-calculate and evaluate the seasonal fluctuation of Sudd areas on the basis of time series analysis and compare it with results of previous studies.

1.2 Research Problems

The recent shortfalls of rainfalls over Ethiopia (Blue Nile) and the population increase in the Sudan and Egypt made the swamp area in southern Sudan under focus (Howell *et al.*, 1996).The swampy area reclamation is considered as a potential water resource of Sudan and Egypt, about 6.0 million cubic meters of water will be saved for Sudan from the swampy area reclamation (Eldaw, 2003). The total water losses annually at Sudd area on the other hand is, estimated to be 14 km^3 / year (Howell *et al.,* 1996). This let the water losses at Sudd swamp area to be the sources of debate of many water's planners, researchers and managers in the past and present days. Many studies about the swampy areas evaporation amount have been carried out (Sutcliffe *et al*., 1999; Mohammed *et al*., 2005), which were resulted in a confusing or a contradictory result. That is no consensus on evaporation estimation and area inundated has been reached (Shamseddin, 2006).

The following are pinpointed as the main problems in study area:

1- Currently there is a severe lack of adequate data and information relating to the Sudd region that can assist, for the further development and management.
2- The dynamics of the Sudd fluctuation is not well understood for further development and analysis.
3- The water spread area is not properly delineated and demarked.
4- The temporal and spatial fluctuation of the Sudd over seasons is not well understood.
5- The above mentioned problems are the indication for few research studies has been undertaken at the Sudd area.

1.3 Research questions

The following are the main questions needed to be answered in this study:

1- What are the dominant components of the hydrological cycle controlling the hydrological behavior of the Sudd swamp?
2- Does the Sudd water volume increase or decrease? If so, can it be explained in terms of water balance model?
3- How does the Sudd area will have impacts on the various the developmental human activities in future?

1.4 Objectives of the study

General objective

The main objective of the study is to assess the temporal and spatial variation of hydrological dynamics (runoff and change in storage) of Sudd area using water balance technique for the period of 1950 to 2009.

Specific Objective

To this end the following specific objectives were planned to be carried out:

1- Assessment of the temporal and spatial variation of the Sudd flooding volume and, flooding area using water balance technique.

2- To estimate the total water yield of the out flow of the Bahr el Ghazal , Bahr el Jebel and Sobat rivers .

3- Evaluation, reconstruction and estimation of evaporation over inside the Sudd area using appropriate methods.

4- Assessment of the Sudd Swamp flooding area sensitivity to the variation of the climate change and human activities.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 The Hydrologic cycle

The hydrological cycle is the most important carrier of water, energy and matter (chemical, biological materials, sediments, etc), locally and globally. The hydrological cycle acts like an enormous global pump that is driven mainly by two forces; solar energy and gravitation pull. Humans have ingeniously utilized this global and free pump to get irrigation water and to draw power from the enormous of energy that this cycle represents (Ojha, *et al,* 2008).

The incoming solar energy forces water to evaporate from both land and sea. Much of this vapour condensates and falls directly over the sea surface again (globally about 7/8 of the rainwater falls over the oceans). The remainder of the rainwater falls over land (globally 1/8), and it falls as precipitation (rainfall, snow, and / or hail). This forms runoff as creeks, rivers, lakes and swamps on the soil surface. A major part, however, infiltrates through the soil surface and form soil water that may later percolate down to the groundwater level. In the ground water can also be taken up by plant roots, and evaporate into the atmosphere through transpiration or by direct evaporation from soil. The total evaporation from both soil and plant is called evapotranspiration (Ojha, *et al*, 2008).

Humans influence and change the general hydrological cycle to a great extent. Activities in the landscape directly affect the different components of the hydrological cycle. The chemical content of different hydrological parts is also increasingly affected by various activities such as industry, agriculture and city life. Yet, total water on earth is constant. Water is neither created nor is disappearing from earth.

2.2 The Water Balance

The basis for availability and general transportation of water and pollutants for a specific area is called the water balance or mass balance equation or continuity equation. The water balance in general, stipulates that all inflow minus all outflows to an area during a certain time period must be equal to the storage change (Ojha, et al, 2008). The water balance model contents different time scale, daily, weekly, monthly and yearly time's scales are mostly use. Monthly water-balance models have been used as a means to examine the various components of the hydrologic cycle (for example, precipitation, evapotranspiration, and runoff) (McCabe and Markstrom 2007). Such models have been used to estimate the global water balance; to develop climate classifications (Thornthwaite, 1948); to estimate soil-moisture storage (Alley, 1984 ;); runoff (Alley, 1984,), and irrigation demand (McCabe and Wolock, 1992); and to evaluate the hydrologic effects of climate change (McCabe and Ayers, 1989 ;)

The major components of the hydrological cycle are the inflow, outflow and change in storage. Inflow is amount of water that falls or enter into area (precipitation , runoff) the outflow are all water that leave the area (runoff leaving the area , Evaporation) change in storage is amount of water that modify the total water storage of the area .

The water balance combines separate elements of the water cycle and allows one to study them together in one complex and to estimate changes brought about by disturbance of the natural cycle. Water balances of water bodies are used for solving practical problems, which is necessary for water resources development. From the various uses of water balance run off simulation using metrological data is the primary one for hydrologists and water resource engineers. In order to achieve the above uses initial and direct observation data are required for different parameters in the water balance equation. In view of the fact that data from Sudan like most of the developing countries are inadequate or scarce and are more likely to contain large observational errors.

The water balance approach has many applications in water resources development. It is used to analyze the availability of the water in the area, like to find out how much water is available that can be used for drinking purpose or irrigation. It applies also to calculate the evaporation when there is lack of the meteorological data.

2.3 Water Balance Equation

2.3.1 Watershed water balance equation

Different literatures describing water balance model are available, they have common board on the concept of the water balance, with some different, on application purpose, time scale and spatial scale. The common one is the one developed by Thornthwaite, which is base on monthly time scale, and consider different environment conditions. The water-balance model (fig. 2.1) analyses the allocation of water among various components of the hydrologic system using a monthly accounting procedure based on the methodology originally presented by Thornthwaite. Inputs to the model are mean monthly temperature (*T*, in degrees Celsius), monthly total precipitation (*P*, in millimeters), and the latitude (in decimal degrees) of the location of interest. The latitude of the location is used for the computation of day length, which is needed for the computation of potential evapotranspiration (*PET*). The model is referred to as the Thornthwaite model.

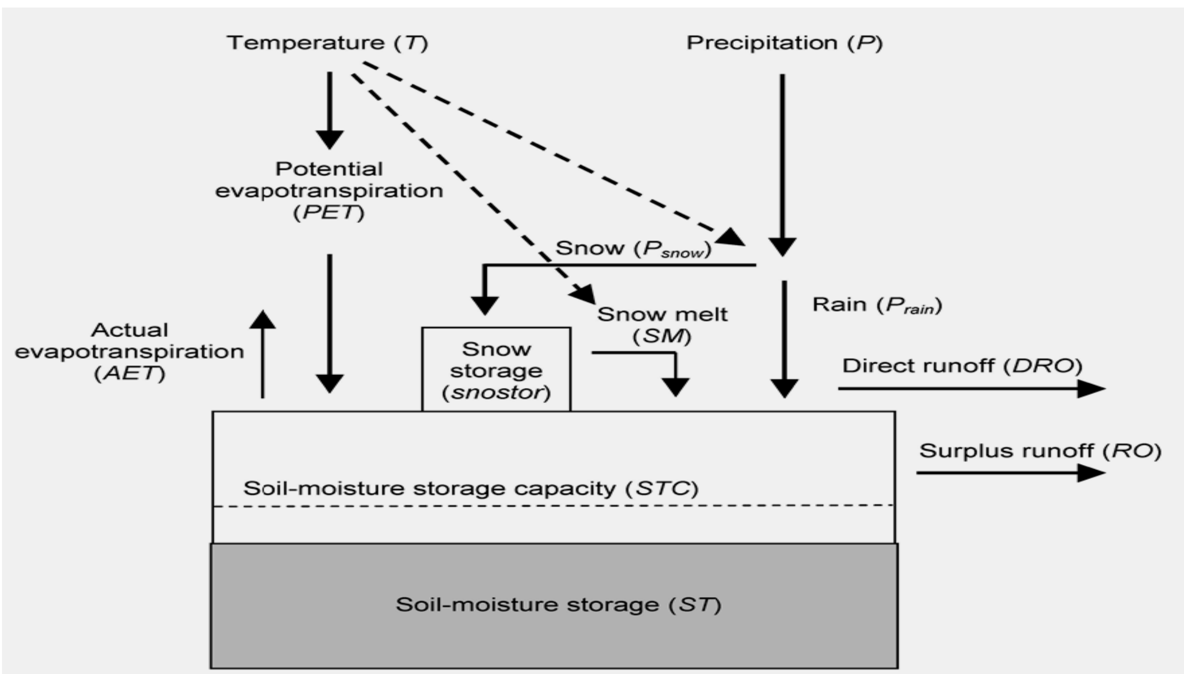

Figure2. 1: Diagram of the water-balance model (sources (McCabe and Markstrom 2007)

A discussion of the individual components of the water balance follows.

1- Snow Accumulation and Snow Melt

The first computation of the water-balance model is the estimation of the amount of monthly precipitation (*P*) that is rain (*Prain*) or snow (*Psnow*), in millimeters. When mean monthly temperature (*T*) is below a specified threshold (*Tsnow*), all precipitation is considered to be snow. If temperature is greater than an additional threshold (*Train*), then all precipitation is considered to be rain. Within the range defined by *Tsnow* and *Train*, the amount of precipitation that is snow decreases linearly from 100 percent to 0 percent of total precipitation. This relation is expressed as:

$$P_{snow} = P \times \left[\frac{T_{rain} - T}{T_{rain} - T_{snow}} \right] \qquad 2.1$$

P_{rain} then is computed as: $P_{rain} = P - P_{sonw}$

But here in our case we only consider the rainfall, while the snow is equal zero.

The fraction of *snostor* that melts in a month (snow melt fraction, *SMF*) is computed from mean monthly temperature (*T*) and a maximum melt rate (*meltmax*); *meltmax* is often set to 0.5(McCabe and Markstrom 2007). The fraction of snow storage that melts in a month is computed as:

$$SMF = \frac{T - T_{snow}}{T_{rain} - T_{snow}} \times melt\max \qquad 2.2$$

If the computed *SMF* is greater than *meltmax*, then *SMF* is set to *meltmax*. The amount of snow that is melted in a month (*SM*), in millimeters of snow water equivalent, is computed as: $SM = snostor \times SMF$

SM is added to *Premain* to compute the total liquid water input (*Ptotal*) to the soil.

2- Direct Runoff and runoff generation

Direct runoff (*DRO*) is runoff, in millimeters, from impervious surfaces or runoff resulting from infiltration-excess overflow. The fraction (*drofrac*) of *Prain* that becomes *DRO* is specified; based on previous water-balance analyses, 5 percent is a typical value to use (McCabe and Markstrom 2007). The expression for *DRO* is:

$$DRO = P_{rain} \times drofrac \qquad 2.3$$

Direct runoff (*DRO*) is subtracted from *Prain* to compute the amount of remaining precipitation (*Premain*): $P_{remain} = P_{rain} - DRO$ 2.4

Runoff (*RO*) is generated from the surplus, *S*, at a specified rate (*rfactor*). An *rfactor* value of 0.5 is commonly used (Wolock and McCabe, 1999). The *rfactor* parameter determines the fraction of surplus that becomes runoff in a month. The remaining surplus is carried over to the following month to compute total *S* for that month. Direct runoff (*DRO*), in millimeters, is added directly to the runoff generated from surplus (*RO*) to compute total monthly runoff (*ROtotal*), in millimeters.

3- Evapotranspiration and Soil-Moisture Storage

Actual evapotranspiration (*AET*) is derived from potential evapotranspiration (*PET*), *Ptotal*, soil-moisture storage (*ST*), and soil-moisture storage withdrawal (*STW*). Monthly *PET* is estimated from mean monthly temperature (*T*) and is defined as the water loss from a large, homogeneous, vegetation-covered area that never lacks water (Thornthwaite, 1948; Mather, 1978). Thus, *PET* represents the climatic demand for water relative to the available energy. In this water balance, *PET* is calculated by using the Hamon equation (Hamon, 1961):

$$PETH = 13.97 \times d \times D^2 \times W_t \qquad 2.5$$

Where *PETH* is *PET* in millimeters per month, *d* is the number of days in a month, *D* is the mean monthly hours of daylight in units of 12 hrs, and *Wt* is a saturated water vapor density term, in grams per cubic meter, calculated by:

$$W_t = \frac{4.95 \times e^{0.062 \times T}}{100} \qquad 2.6$$

Where *T* is the mean monthly temperature in degrees Celsius (Hamon, 1961)

When *Ptotal* for a month is less then *PET*, then *AET* is equal to *Ptotal* plus the amount of soil moisture that can be withdrawn from storage in the soil. Soil-moisture storage withdrawal linearly decreases with decreasing *ST* such that as the soil becomes drier, water becomes more difficult to remove from the soil and less is available for *AET*.

STW is computed as follows:

$$STW = ST_{i-1} - \left[abs\left(P_{total} - PET\right) \times \left(\frac{ST_{i-1}}{STC}\right)\right] \qquad 2.7$$

Where *STi*-1 is the soil-moisture storage for the previous month and *STC* is the soil-moisture storage capacity. An *STC* of 150 mm works for most locations (McCabe and Wolock, 1999; Wolock and McCabe, 1999). If the sum of *Ptotal* and *STW* is less than *PET*, then a water deficit is calculated as *PET–AET*. If *Ptotal* exceeds *PET*, then *AET* is equal to *PET* and the water in excess of *PET* replenishes *ST*. When *ST* is greater than *STC*, the excess water becomes surplus (*S*) and is eventually available for runoff.

2.3.2 Lake or Reservoir water balance equation

The input and output components of the water balance of a lake or reservoir depend not only on the physical dimension of the water body, but also on the climatic, hydrological and geological factors affecting the water body and its surrounding areas (Awulachew 2001). The water balance equation can be written, from continuity equation at any time, which is governed by the conditions that the water volume remains constant. The continuity equation in turn governed by conservation of matter, which described by equilibrium between added water volume or depth, lost water volume or depth and change in volume or depth as:

$$V_{in} - V_{ou} + P - E - \Delta S = 0 \qquad 2.8$$

Where V_{in} is surface and subsurface inflow; V_{ou} is surface and subsurface outflow; P is precipitation volume; E is evaporation volume; ΔS is change in storage.Alternatively, parameters can also be similarly defined in terms of depth of water. In ideal situation variables of the water balance equation are computed separately, and providing closed result. In practice however, the computation leads to a discrepancy or residual error. Considering the error term, δ, the above equation can be re-written as:

$$V_{in} - V_{ou} + P - E - \Delta S \pm \delta = 0 \qquad 2.9$$

In the above equations parameters can be distributed as:

$$V_{in} = V_{si} + V_{ssi}\ , \qquad V_{si} = \sum_{i=1}^{ngw} V_g + \sum_{i=1}^{nuw} V_{ug}\ , \qquad V_{ou} = V_{so} + V_{sso}$$

Where respectively, V_{si} and V_{so} are sums of surface inflow and outflow; V_{ssi} and V_{sso} are sub-surface inflow and outflow; V_g are V_{ug} are gauged and ungauged inflows; *ngw* and *nuw* are number of gauged and ungauged watersheds. The error term, *δ*, is treated component wise.

2.4 Water balance of Bahr el Jebel

The areal size of the sub-basins is one of the key problems for assessing the water balance (Mohammed et al., 2004). The Sudd swamps results from water spillage on both sides of the Bahr el Jebel River, and it extends from near Juba up to the confluence with the Sobat River just upstream Malakal. There is an ongoing debate on the catchment boundaries, which cannot be straightforwardly surveyed because of its immense dimensions and because the area is not freely accessible. The area of the Sudd swamps shrinks and swells during the season. The boundary between the Sudd and Bahr el Ghazal swamps is highly questionable, and some hydrological state parameters should be used to help identifying the boundaries. The area of the Bahr el Jebel sub-basin has been estimate by Mohammed 2004 using the evaporation map abstract from SEBAL satellite images. The estimating area is 38.3 Billon m2.

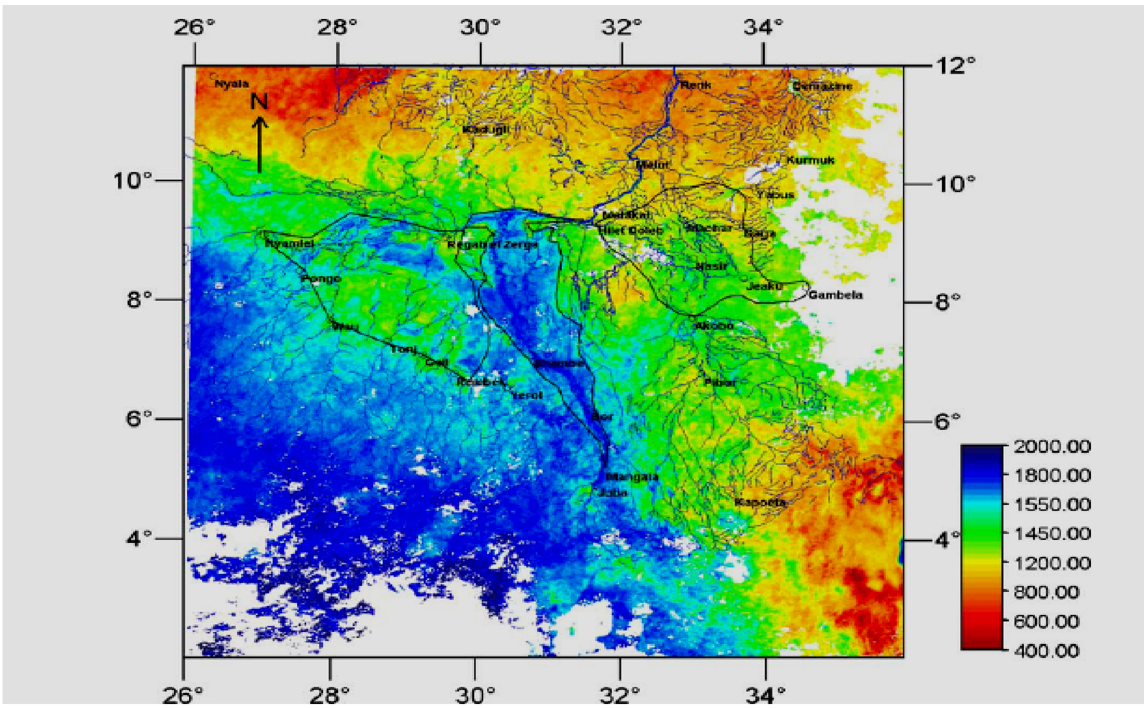

Figure2. 2 Delineation of the Sudd using evaporation map (Source Mohammed 2004)

The estimation of the water balance of the Sudd is done by using the equation made by Sutcliffe and Parks 1999. The formulation of the water balance is as follows:

$$dV = [Q_{in} - Q_{out} + A(P - E) - rdA]dt \qquad 2.10$$

Where V is the storage, Qin is inflow, Qout is outflow, P is rainfall, E is evaporation, A is the flooded area and r is soil moisture recharge. Note that the recharge pertains to expanding areas dA only. A linear relation between A and V is assumed to eliminate two unknowns from the equation. The result of water balance was found annual storage change dv/dt is -1.15 BCM/yr.

2.5 Water balance of Bahr el Ghazal

A preliminary water balance of the Bahr el Ghazal swamps was outlined in The Nile Basin, vol. V (Hurst & Phillips, 1938), with measured flows of the Jur at Wau supplemented by estimates for the other tributaries. The average flow of the Jur at Wau was assessed as 5.0 km3, based on levels from 1912 to 1932 and discharge measurements in 1930-1932. From rainfall estimates of 1140-1450 mm over the useful catchments, the total average runoff from the Bahr el Ghazal tributaries was estimated as 15.7 km3, with an additional 2.7 km3 from the Bahr el Jebel tributaries. These total flows were compared with estimated evaporation from the areas of swamps in the lower Bahr el Ghazal basin, estimated from survey maps. The total area of the Bahr el Ghazal swamps, including those fed by the Bahr el Jebel tributaries, was tentatively assessed as 16 700 km2, from which the net evaporation loss was deduced as slightly over 1 m, plus 0.8-0.9 m average rainfall. At the same time, Mohammed (2004) had been studying the water balance of the Bahr el Ghazal sub-basin and had deduced area of the basin as 59.27 Million m2; this on the basis of the streams and location of gauging stations (Fig. 2.3).

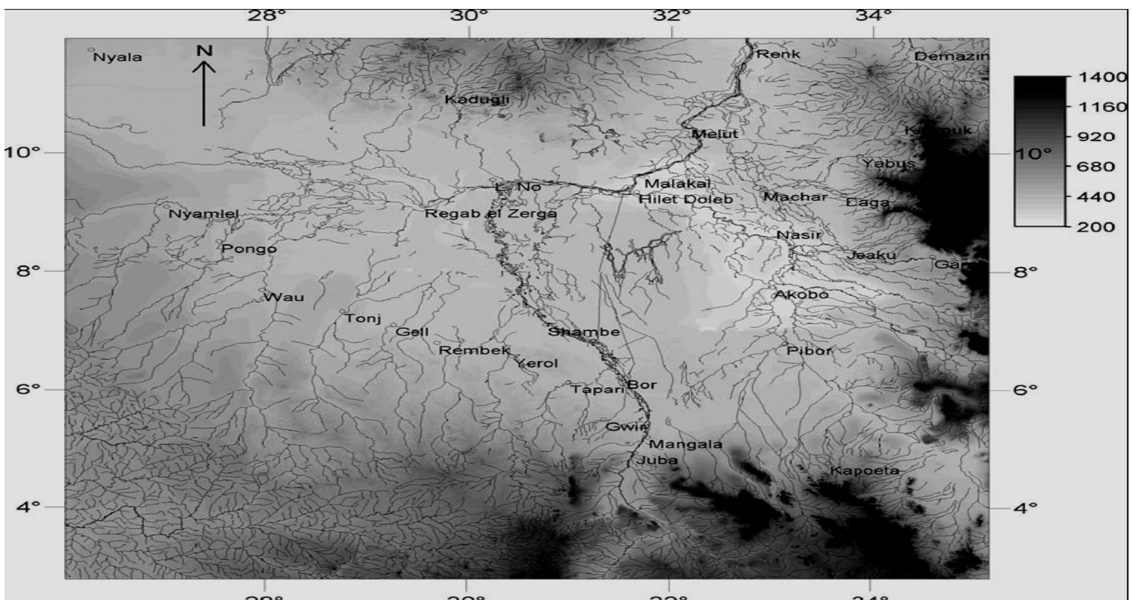

Figure2. 3: location of hydrolo-metrological stations (Source Mohammed 2004)

The boundaries are hydrologically correct, but the total area could be easily expanded if more streams are included. The gauging stations used for the delineation are Nyamlel on the Lol River, the Road Bridge across the Pongo River, Wau on River Jur, Tonj on River Tonj, and the Road Bridge across the Maridi River near Rumbek and Mvolo on River Naam. Although these streams have been gauged starting from the 1930s and 1940s, measurements at high flows are very limited. It is probable that during high flows, these stations underestimate flows that bypass the gauge over the inundated land. The rivers flowing to Bahr el Jebel, The monthly water balance using SEBAL evaporation volumes formulated according to Equation 2.11 , shows a shortfall of dV/dt = -24.48 Gm3/yr (Mohammed 2004).

$$\frac{dV}{dt} = (Q_{in} + R) - (Q_{out} + E)) \qquad 2.11$$

2.6 Sobat water balance

It has to be noted that, inflow and outflows to the Machar swamp area, used in earlier studies differ appreciably from one study to another. The Jonglei investigation team (1954) estimated annual spill of 2.8 Gm3/yr (G = 10^9) from Baro towards Machar Marches, plus annual flow of 1.7 Gm3/yr from the eastern catchment, and an outflow of 0.5 Gm3/yr. Sutcliffe and Parks (1999) in their investigation of the flow records between 1950 and 1955 estimated flows to the Machar marches as: 2.3 Gm3/yr spill from Baro, 1.7 Gm3/yr from eastern streams, and outflow of 0.12 Gm3/yr.

The Sobat contributes to about half of the White Nile flows at Malakal (13 Gm3/yr). The catchment boundary given in Fig. 3.2 has been delineated from the gauging stations of Akobo, Gambela, Daga and Yabus up to the confluence near Malakal (Mohammed 2004). The outflow is defined at the Sobat mouth (Hillet Dolieb). Outflow to the Nile north of the Machar marches through Khor Adar and Khor Wol is believed to be negligible. The inflow constitutes river discharges from Baro at Gambela, Pibor at Akobo, Akobo at Akobo, Gila, Mekwai, Jeakau, and the eastern streams of Dagga and Yabus . About 13 Gm3/ yr comes from Baro at Gambela, and only 5 Gm3/yr comes from the other streams (Sutcliffe and Parks, 1999).

On an annual basis, dV/dt computed according to Eq. (2.11) becomes dV/dt = -3.12 Gm3/ yr. The monthly variation of dV/dt based on soil moisture computations shows distinct temporal variation in the Sobat sub-basin, but confirms negligible annual change of storage. The annual dV/dt closure term amounts to 5.7% of the annual evaporation within the confidence limits of the collected longer-term average flow data (Mohammed 2004).

2.7 Estimation of the potential Evaporation

Different methods for the estimation of the evaporation are available in many literatures, here the some detail are given for the two methods, Penman and Thronthwaite:

2.7.1 Penman Combination

This method was developed to determine the potential evapotranspiration (PET) of a specific area, depending on its climatic and meteorological conditions. The Penman equation is a combination of energy balance and wind transfer, which reads (Subramanya, 1994)

$$ETP = \frac{(AH_n + E_a\gamma)}{(A+\gamma)} \qquad 2.12$$

Where, ETP = daily potential evaportranspiration (mm/day)

A = slope of the saturation vapour pressure vs. temperature curve at air temperature mm Hg/C^o

H_n = net radiation (mm/day) (meteorological table)

γ = the psychometric constant (0.49 mm Hg/ C^O)

H_n is estimated from the following equation:

$$H_n = H_a(1-r)\left(a + b\frac{n}{N}\right) - \sigma T_a^{\ 4}(0.56 - 0.092\sqrt{e_a})(0.10 + 0.90\frac{n}{N}) \qquad 2.13$$

H_a = incident solar radiation outside the atmosphere on a horizontal surface (mm/day)

r = albedo of the surface giving the reflection at soil or water surface of income energy.

a = constant equal to 0.29cos (¢), ¢ = latitude

b = constant approximately equal to 0.52

n = actual duration of bright sunshine (hours / day)

N = maximum possible duration of bright sunshine (hours/day)

σ = Stefan –Boltzmann constant

T_a = mean air temperature in K^O i.e., (273+C^O)

$e_{a\,=}$ actual mean vapour pressure in the air (mm Hg)

E_a is calculated according to:

$$E_a = 0.35\left(1 + \frac{u_2}{160}\right)(e_s - e_a) \qquad 2.14$$

Where, u_2 = mean wind speed at 2 m above the ground (km/day) and e_s = saturated vapour pressure in the air (mm Hg)

2.7.2 Thronthwiate method

Is widely used method for estimating potential evapotranspiration, was derived by (Thornthwaite,1948),who correlated mean monthly temperature with evapotranspiration as determined from water balance for valleys where sufficient moisture water was available to maintain active transpirationm (Xu and Singh 2001). The annual value of the heat index I is calculated by summing monthly indices over a 12 month period. The monthly indices are obtained form the equations.

$$i = \left(\frac{T_a}{5}\right)^{1.51} \quad \text{And} \quad I = \sum_{j=1}^{12} i_j \qquad 2.15$$

In which I is the annual heat index, i is the monthly heat index for the month i (which is zero when the mean monthly temperature is 0^0 c or less), Ta is the mean monthly air temperature (^{0}c) and j is the number of months (1 - 12).

The Thornthwaite general equations, calculates unadjusted monthly values of potential evapotranspiration. ET^1 (in mm). Based on a standards month of 30 days, 12h of sunlight / days

$$ET^1 = C\left(\frac{10\ Ta}{I}\right)^a \qquad 2.16$$

In which c = 16 (a constant) and a = $67.5 \times 10^{-8} I^3 - 77.1 \times 10^{-6} I^2 + 0.0179 I + 0.492$.

The value of the exponent a in the preceding equation varies from zero to 4.25 the annual heat index varies from zero to 160, and ET^1 is zero for temperature below $0\ ^0$ c. From these observations it is seen that there is no simple relationship between monthly evapotranspiration and monthly temperature (Thornthwaite, 1948). The coefficients ***c*** and a vary from one place to another. Thus an equation having coefficients derived from observations made in a warm climate does not yield correct values of potential evapotranspiration for an area having a cold climate, and vice versa.

At lower temperatures there is increasing divergence in potential evapotranspiration. In a general equation constants *c* and a must be allowed to vary with a factor that is small in cold climates and large in hot climates. Mean annual temperature is not satisfactory because in some places it is affected by below-freezing temperatures. **A** special equation was developed for the purpose (Thornthwaite 1948).

The unadjusted monthly evapotranspiration value ET[1] are adjusted depending on the number of days N in a month $(1 \leq N \leq 31)$and the duration of average monthly or daily day light d (in hours), which is a function of season and latitude

$$ET = ET^1 \left(\frac{d}{12}\right) \left(\frac{N}{30}\right) \qquad 2.17$$

In which ET is the adjusted monthly potential evapotranspiration (mm),d in the duration of average monthly daylight (hr) and N is the number of days in a given month, 1-31(days).Thornthwaite`s equation was widely criticized for its empirical nature but is widely used.

2.8 Uncertainty in the Water Balance

The accuracy of the water balance results is a function of the accuracy of the inputs data and the degree to which the water balance equation represents the hydrological process appropriate to the problem (Awulachew, 2001).The uncertainties in estimating the water balance of the lake or reservoir is rising due to errors on the estimation of the input data (Winter 1981).

Estimates of precipitation can have a wide range of errors, depending on gauge placement, gauge spacing, and aerial averaging technique. The amount of rainwater collected and measured by a rain gauge may not always represent the exact amount, which would have been caught. For example there may be instrumental errors in the gauges, or in their recording or measuring arrangements; some rainwater may get lost due to splash from the collector; some water from an initial rain may got lost in moistening the gauge funnel and other inside surfaces; blowing winds may tilt the rains from vertical, thus bringing lesser catch in the vertical gauge; dents in the collector rim may change its receiving area; vertical upward air currents may impart upward acceleration to precipitation this bringing lesser catch in the gauge; etc.

All such factors try to introduce errors in the measured catches. Some of them may increases catch, and some of them may decrease the catch. However, in general, it can be stated that almost all the errors that are introduced in the rain catch measurements have a tendency to yield measurements which are too low. In other words, the observed rain catch needs to be increased for the likely errors introduced in its measurement.

Of all the possible errors the most serious errors is introduced by wind, which may result in a vertical acceleration of air, forced upward over the gauge. Higher the gauge, greater will be the wind errors, and hence more deficient will be the rain catch. Errors in estimate of evaporation can also vary widely depending on the instrumentation and methodology. The energy budget is the most accurate method of calculating evaporation with errors of the orders of 5% when applied to periods less than a week. If pans are used that are located at a distance from the lake of interest, errors can be considerable (Mazengia, 2008).

Finally, both random and systematic errors in rainfall affect and have serious impact on performance of water balance models (Awulachew, 2001).

2.9 Previous Studies on the Area

So many studies have been carried out in the Upper White Nile that includes the study area. These studies have been focusing on water loss due to evaporation, assessment of the water recourses, hydrology and swamp area estimation, which some are directly or indirectly related to the current study. Some of the works are briefly described as follows:

Sutcliffe and Parks 1987 studied on the effect of the Jonglei canal on areas of flooding of sudd swamp using water balance of sudd represented by hydrological model for a period from 1905 to 1980.

Mohamed et al., 2004 used the SEBAL model (Surface Energy Balance Algorithm for Land) to study the area covering the swamps of the Sudd, Bahr el Ghazal and the Sobat sub-basins. The actual evaporation and soil moisture for an area have been investigated. Monthly (actual) evaporation and soil moisture maps for the year 2000 have been generated.

Mohammed 2005 in his study, a regional climate model applied to the Nile Basin, with a special modification to include routing of the Nile flood over the Sudd. The impact of the wetland on the Nile hydroclimatology has been studied by comparing two model scenarios: the present climatology (without drained by Jonglei canal) and a drained Sudd scenario (drained by Jonglei canal).

Sutcliffe and Parks 1989 also studied the water balances of four major African wetlands - Senegal, Niger, Sudd and Okavango - compared through analysis of inflows and outflows, rainfall and evaporation. Annual and seasonal inflows are compared and marked differences are revealed, a simple relation between flooding area and volume is included in the water balance model in order to estimate monthly series of flooded areas over the period of records.

CHAPTER THREE

3. DESCRIPTION OF THE STUDY AREA

3.1 Location and Accessibility

The study area is located in the center of south Sudan between $4^0 to 10^0 N 26^0 to 33^0 E$, extending from Mongalla in the South up to Malakal in the North. There are three basins nearby the study area (see chapter 2), Bahr el Ghazal basin on the west extends from the Nile– Congo divide and joins the Sudd at several places. The Sobat Basin on the eastern side starts from the Ethiopian Plateau and joins the Nile at Malakal; it also spreads northward into the Machar marches (Mohammed 2004) fig 3.1 and Bahr el Jebel basin in the middle of south Sudan.

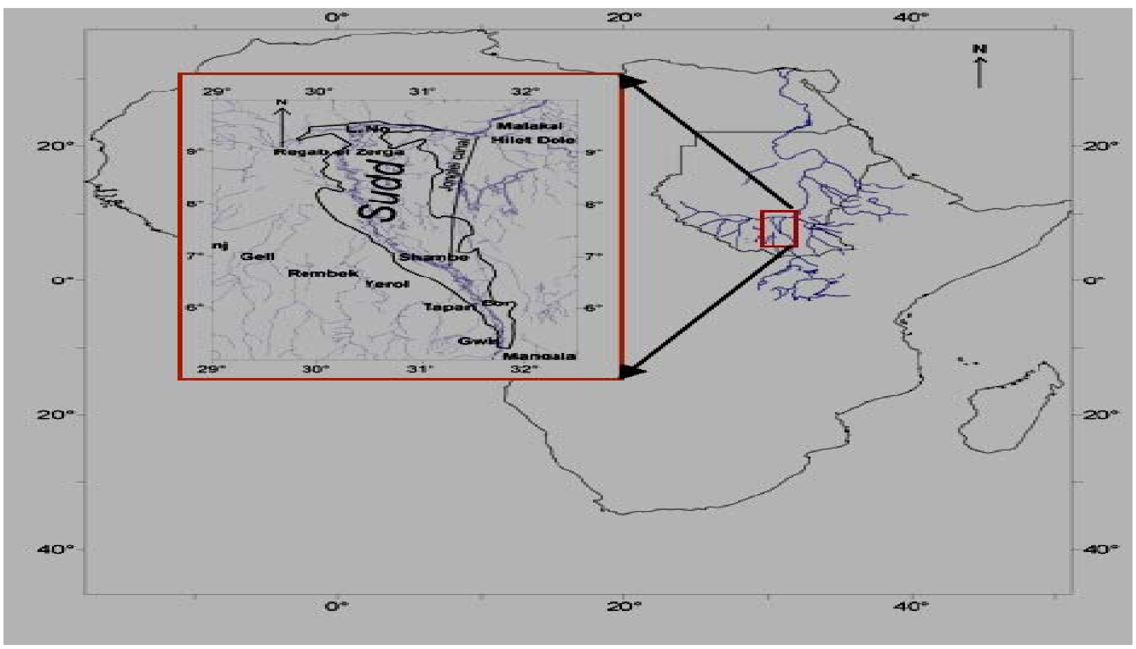

Figure3. 1: Location of study area (Source Mohammed)

3.2 Population

3.2.1 Human

According to the available census data, Sudan's total population in 2008 stands at 39,154,490 (Northern Sudan is 23,378,555 or 59.71%, of the total population, Darfur is 7,515,445 or 19.19% of the total population and Southern Sudan is 8,260,490 or 21.10% of the total.(Jibril ,2010)

The table 3.1 shows the historical statistic of the population in the study area

Ta Table3. 1: Population in study area (Howell, Lock & Stephen 1988 and 2008 from Jibril)

Source	Census Year	District in side Sudd boundaries					Total
		Bor	Kongor	Ayod	Fangak	Watt	
JIT, 1954	1952	58,139	65,453	36,040	65,038	67,275	291,945
SDIT, 1955	1954	67,905	77,300	47,135	73,725	74,750	340,815
National Census	1956	130,620		108,331		103,638	342,589
JEO, 1976a	1955/6 & 1973	48,620	81,000	97,948		53,638	281,206
ILACO, 1975	1973	49,700	Excluding Bor town				
ILACO, 1975	1976	57,000	Excluding Bor town				
ILACO, 1979b	1979	44,990	Excluding Bor town				
World Fertility Survey	1973/79	95,127	92,895	58,925	66,697	68,404	382,048
JEO, 1983	1979/81	92,044	91,112	56,757	66,634	51,889	358,436
Sudan commission of Census	2008	221,106	85,349	139,282	110,130	65,588	621455

3.2.2 Livestock and fisheries

Livestock production represents a significant proportion of agricultural activity, and is directly affected by land and public investment policies, particularly as these apply to migratory grazing and trading routes (MDTF, 2006). Estimates of cattle population in Southern Sudan varies from 8-10 million. The cattle to human population ratio is said to be one of the highest in Africa. Livestock is an important economic asset, in addition to having cultural value. Ownership of cattle is also a risk management tool for pastoralists and farmers, the latter continually facing uncertainty caused by crop failure.

The extreme seasonal variability of climate and in particular the dry season which extends from December to April (Sutcliffe and Parks 1987) make the seasonally flooded land or "Tuich" a vital component of the grazing cycle for the herds of the Nuer and Dinka in particular (the main tribes in the area). They migrate from so-called high land during the rain season to intermediate land or rain-flooded grasslands at the end of the rains and also at the beginning of the rain season. They move to seasonally flooded floodplains of the main river and to a lesser extent other water courses during the main dry season. The short and relatively unreliable nature of the rainfall regime makes livestock an important part of the economy, and there is no alternative to the toich in a grazing economy without recourse to irrigated grassland.

Estimate for the fisheries production potential along the River Nile and particularly in the Sudd region range between 100,000 to 300,000 tons per year on a sustainable basis, which is on par with Lake Victoria's current fisheries production (MDTF, 2006). This estimate is based on the combined water surface area of over 90,000 sq. km in the River Nile and 16,500 sq. km in the Sudd area.

3.3 Physiography and Drainage

Topographically Sudd area was divided into three categories (Sutcliffe and Parks 1987): High land (Free flooded), the intermediate land (seasonally flooded) and Permanent swamp (Always under water). The area is totally described as flat area, which its elevation is around 200 to 350 meter above sea level. Because the flooding regimes of the different parts of the Sudd vary, some description of the topography is needed to understand the hydrology (Sutcliffe and Parks 1999).

The river is incised within an even plain sloping gently north or slightly east of north, while the Bahr el Jebel north of Gemmeiza runs west of north at an angle to the ground slope (fig 2.2). North of Juba the river runs in an incised trough, bounded by scarps with a rise of a few meters marking the limit of the woodland on either flank. The scarps decrease in height from south to north, and disappear just north of Bor on the east bank and south of Shambe on the west.

The Bahr el Jebel is the most complex of the Nile reaches as it receives inflows from a number of seasonal torrents which are not measured directly; it loses water by spill from the river into adjacent flood plains at a rate which can only be inferred by measurements at intervals down the course of the reach; its outflow is only about half the inflow on average and has a totally different seasonal distribution , inflow of the sudd is measured at Mongalla while the outflow is measured at Malakal (Sutcliffe and Parks, 1999).

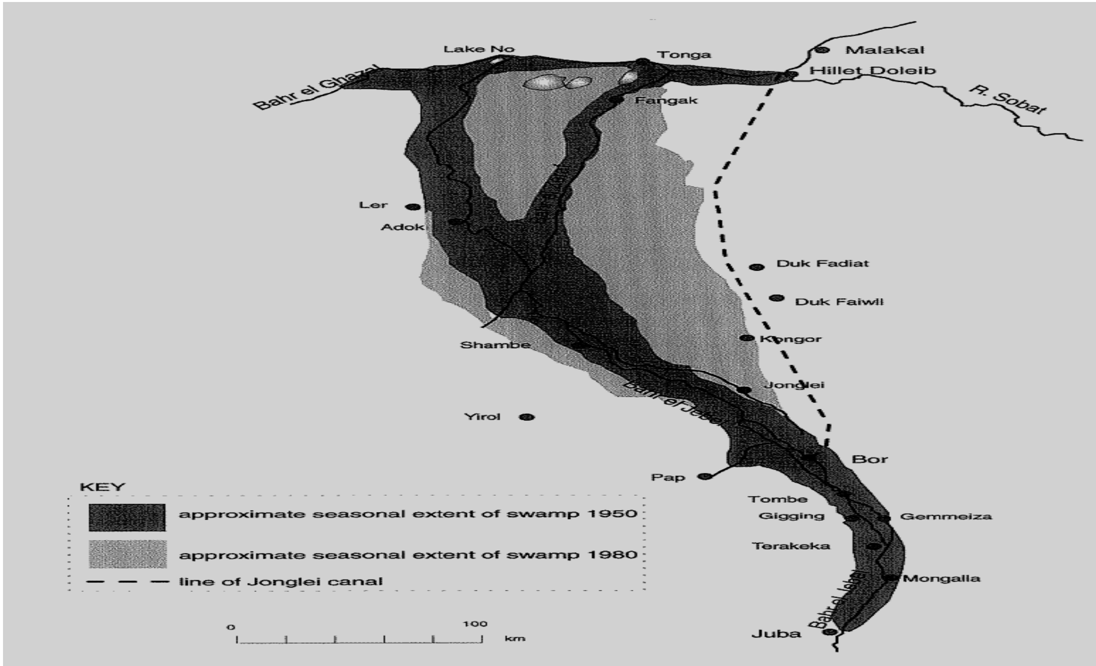

Figure3. 2: Inundated area and districts in area (After Sutcliffe and Parks 1999).

3.4 Vegetation and grass cover

Based on observations, vegetation cover of the area can generally be classified in five Categories which occur depending on the elevation above, and distance from the river (Petersen, 2008): Swamp, River flooded grasslands (Tuic), Rain flooded grasslands, wooded grasslands and Woodlands. While the permanent swamp is inundated all year round, the river flooded grasslands get inundated with rising water levels and spill from the swamp. Predominantly grassy species, adapted to long term inundation of several months, are found in these areas. The density of the grasslands is changing depending on the season, being tall grass in the rainy season and short and dry in the dry season, where also frequent fires occur. The fluvial area is generally overgrown with vegetation, with some main and side channels as well as lagoons of open water. Main species include Typha Dominingensis, Phragmites communis, Echinochloa, Pyramidalis, Oryza barthii, Vossia cuspidate and Cyperus papyrus.

We do not yet know how much we may increase or decrease transpiration by varying the type of plants or by modifying the plant cover (Thornthwaite 1948). Since transpiration regulates leaf temperature, and since most plants reach their optimum growth at about the same temperature, we probably cannot change it very much except by reducing the density of the plant cover and thus wasting a part of the solar energy. If all the vegetation is removed from a field, there will be no transpiration. But as long as the root zone of the soil is well supplied with water, the amount of water transpired from a completely covered area will depend more on the amount of solar energy received by the surface and the resultant temperature than on the kind of plants, (and this will be the similar for what will happen in the study area when the swamp water will be drained by Jonglei canal).

The vegetation conditions in the study area were established from observations in the seasonally flooded areas (Petersen. 2008). The grasslands are mainly inhabited by grassy species of which Echinochloa pyramidalis (Antelope Grass), Echinochloa stagnina (Hippo Grass), Vossia cuspidata (Hippo Grass), Oryza barthii (Wild Rice) and Oryza longistaminata (Wild Rice) are the most common ones that have been observed (Petersen. 2008). During the annual cycle of flooding and drying the vegetation follows the pattern of water availability. Growth starts after the first rains in April and reaches its peak in July at the peak of the floods where large areas are inundated and the grass overgrowth the whole water body. With decreasing flood levels also the vegetation deteriorates and dries quickly after the end of the rainfall period. In November the grass starts to burn in patches and by January all grass is burnt with the bare soil exposed until the next growing cycle starts again.

3.5. Climate

General

Features of the study area meteorological stations are presented in (Shahin, 1988, Mohammed 2004). The air temperature reaches its maximum in March /April and gradually declines in July, August and September. The annual average temperature is approximately 28.8C high. The relative humidity has a distinct annual variation, from about 20% in the dry season to 80% in the rainy season. The reference evaporation is computed according to the FAO Penman–Monteith method. The monthly variations show that PET 10 mm/d in the dry season and reduce to, 4 mm/d during the wet season. The accumulated values of ET are 2400 mm/yr for the Juba station and 2900 mm/yr for the Neyala station, respectively (Mohammed 2004). The actual evaporation (AET) is expected to be substantially lower as the basin does not exist of a reference crop (12 cm clipped grass) with ideal moisture regimes throughout the whole year.

Rainfall

The rainfall varies from 1500 mm/yr on the southwestern part of the study area to around 900 mm/yr on the plains, decreasing to 600 mm/yr on the northern part of the area. The rainy season extends from April to October, with the peak in July/August. The distribution of the rainfall in Sudan is dominated by the position of the Intertropical Convergence Zone (ITCZ) (Mohammed 2004). The ITCZ travels to as far as 20.8 N during the peak rainy season July to September, and back to closer to the equator during the period November to March. Rainfall intensities increase southward from the position of the ITCZ. The second influence on the distribution of rainfall after the altitude is the effect of orography; this is clearly shown by the curvature of the isohyets parallel to the Ethiopian Plateau.

Wind speed

The wind speed is important factor that affect the evaporation, it aids in removing the evaporated water vapour from the zone of evaporation and consequently creates greater scope for evaporation. Wind speed measurements in the study area show a range between 21 Km/hr daily average wind speed, showing an annual average value of 2.1 m/s. The highest values occur in April before the start of the rains (Petersen, 2008).

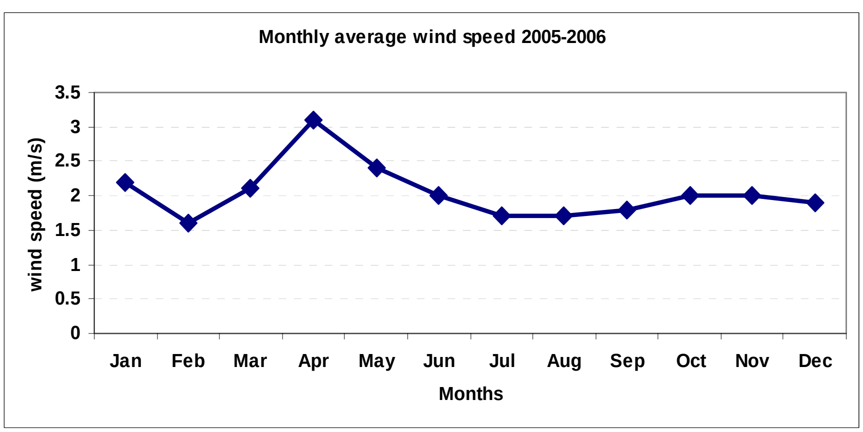

Figure3. 3: Mean monthly wind speed (Petersen. 2008).

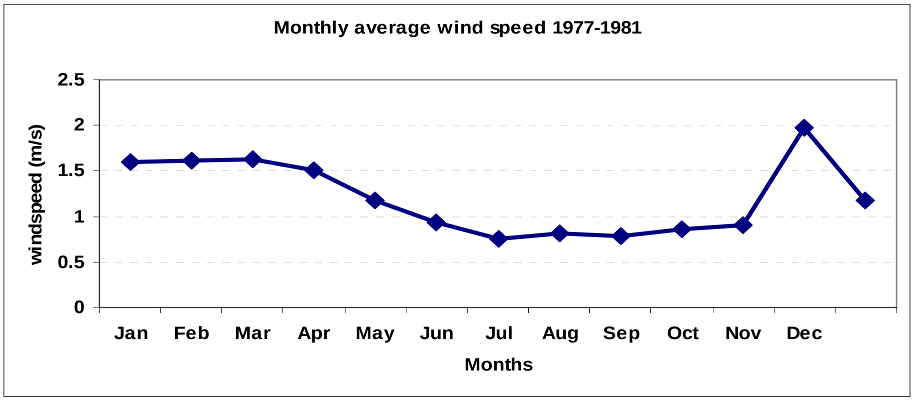

Figure3. 4: Mean monthly wind speed

Relative humidity

The relative humidity over Sudd area ranges between 46 and 89% with the maximum between July to September, and minimum December to February. The figure below show comparison of the mean monthly relative humidity for the station inside Swamp area (Bor) and that outside the swamp area (Malakal, Juba and Wau)

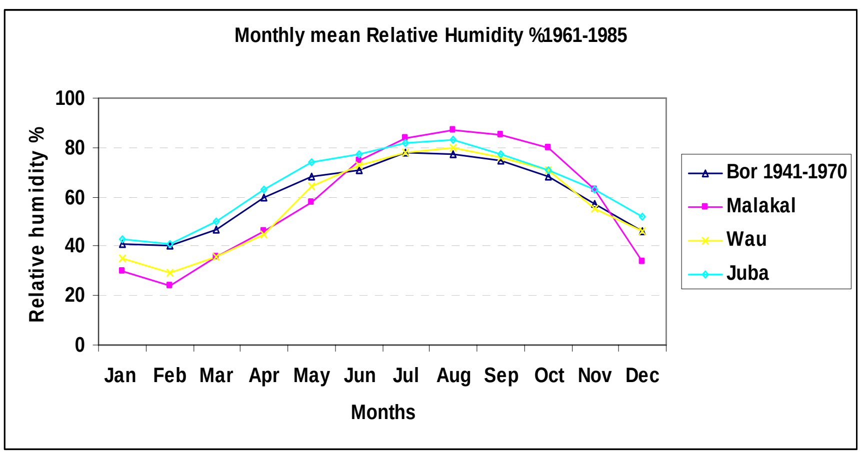

Figure3. 5: Average relative humidity

3.6 Soil

Transpiration and evaporation are both affected in the same way by variations in soil moisture (Thornthwaite, 1948). Both increase with increase of available water in the root zone of the soil, to an optimum. Above the optimum both are less, presumably because of poor aeration of the soil, which results in a lack of oxygen to supply the roots and an excess of carbon dioxide the other hand, as water in the soil increases above the optimum for growth, direct evaporation from the soil surface also continues to increase.The Soil type in the study area is sandy clay loam with highly impermeable conditions. The soil water recharge values vary with rainfall over the season and exceed 350 mm when the soil is dry. (Petersen, 2008)

3.7 Water Resources

The main sources of flowing water to the study area are the tributaries coming from the Ethiopian Plateau receiving summer rainfall originating from the Atlantic Ocean, and the tributaries coming from the Equatorial lakes plateau subjected to spring and autumn rain originating from the Indian Ocean. (Mohammed, 2004), and finally the tributaries of the Bahr el Ghazal coming from Congo Nile water divide. Meanwhile the study is divided into three sub-basins namely; Bahr el Jebel Sudd basin), Bahr el Ghazal, and Sobat, the main characteristics of the three basins are in the table below.

Table3. 2: Main characteristics of the sub-basins (Source Mohammed 2004)

Sub-basin	Area of basin (10^9 m^2)	Catchment cover	Hydrological record
Sudd (Bahr el Jebel)	38.6	Dominated by swamps	Good quality
Bahr el Ghazal	59.3	Mix of swamps and dry land (around 10-20% swamps)	Incomplete , partially gauged
Sobat	42.9	Mostly dry land , with some seasonal swamps	Fair

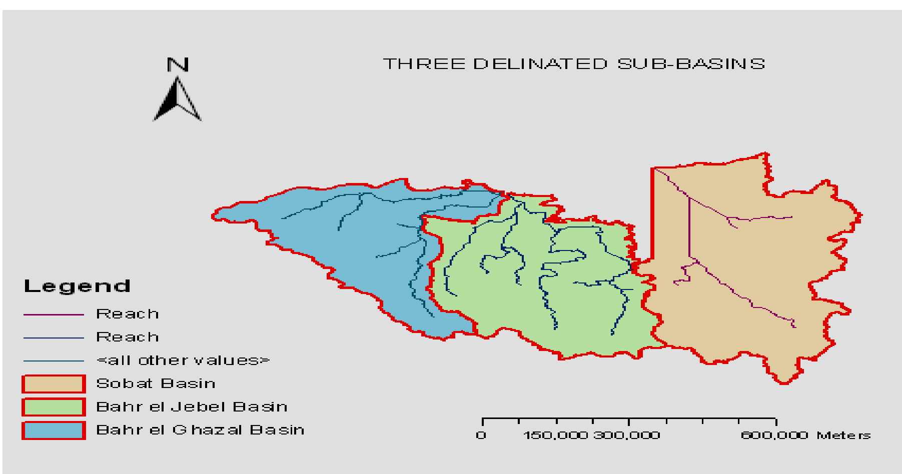

Figure3. 6: Map of the three basins

3.7.1 Bahr el Jebel Basin

3.7.1.1 General

The Bahr el Jebel extends from Lake Albert to the confluence with the Bahr el Ghazal at Lake No where the combined river becomes the White Nile. However, it is hydrologically more logical to take the upper limit at Mongalla, the key gauging station where the river is measured in a single channel as it enters the Sudd, and the lower limit at the confluence of the White Nile and the Sobat, where outflows from the Sudd are measured. The Bahr el Jebel is the most complex of the Nile reaches as it receives inflows from a number of seasonal torrents which are not measured directly; the Bahr el Jebel basin or Sudd basin has ponding water at the surface throughout most of the area, and that apart from some higher located spots, the entire sub-basin is flooded in the wet season, or has very shallow groundwater table. The Sudd is the bottom floor of the White Nile, and the in- and outflow of the Sudd is through the Nile only. The single in and outlet makes the area suitable for water balance determinations (Mohammed, 2004).

3.7.1.2 Hydrology of Bahr el Jebel

The record at Mongalla, where flows have been measured since 1905, is the key record of inflow to the Sudd. Few gauging were carried out at Mongalla between 1905 and 1921, with only 35 measurements in the first 17 years (Sutcliffe and Parks, 1999). More frequent measurements began in 1922, with an annual average of 260 measurements from 1922 to 1931. After 1940, the frequency of gaugings fell to about 2 times a month. To once monthly after 1954 and fewer after 1974.There were gaps from September 1964 to June 1967, at a time when the river flows had doubled, and gaugings ceased in 1984. The flows were derived from a general rating curve from 1905 to 1921, by interpolation between measured discharges from 1922 to 1931, and on annual rating curves from 1932 until 1963. The record for 1964-1967 was based on a mean rating derived for the period 1963-1969, and thereafter on annual ratings; records ceased in 1983. The quality of the flow record must have varied with the frequency of gauging but in general has been reasonable. However, comparisons with upstream records showed that flows in 1963-1964, during the rise in lake levels and a rapid change of rating, were not reliable. Comparison of 1978 flows with gaugings shows that the published flows are incorrect; the provisional flows obtained for the 1982 study are more acceptable (Sutcliffe and Parks 1999).

3.7.2 Bahr el Ghazal Basin

3.7.21 General

The Bahr el Ghazal is unique among the Nile tributaries in that its outflow to the White Nile is almost negligible. The rainfall of 1200-1400 mm in the upper basin is the highest in the Sudan and gives rise to a number of seasonal tributaries, which converge towards the confluence of the Bahr el Ghazal with the White Nile. The tributaries of the Bahr el Ghazal derive their runoff from the higher ground of the Congo –Nile divide, but very little of the river flow reaches the White Nile at Lake No. each of the rivers follows a standard pattern, from an elevated perimeter of rapid runoff with good drainage and some rapids through a zone where the rivers meander between alluvial banks in a defined and wending valley into zone of unrestricted flooding over clay plains (Howell and Allan, 1996). The headwaters of the main tributaries are the Naam, Gel, Tonj, Jur and Lol.

3.7.2.2 Hydrology of Bahr el Ghazal

Since 1970 flows for the Loi at Nyamlel, the Jur at Wau and the Tonj at Tonj were measured by the Sudan authorities (Sutcliffe and Parks, 1999). Although a reasonable number of gaugings were carried out yearly at Nyamlel since 1944, the number of high flow measurements has been limited; the ratings have broadly been stable but there have been some shifts and the flows are not precise. At Tonj, where gaugings began in 1942, the ratings have been reasonably stable and well defined, but in some years there were few high flow gaugings and flows may have been underestimated. At Wau, on the other hand, where gaugings have been regular from 1942, the high flow ratings have been well defined and stable, but the low flow ratings are less well defined. The longest potential flow record in the upper Bahr el Ghazal basin is on the Jur at Wau, where a level gauge was established in 1904. Regular flow gaugings were not begun until 1942, but a total of 21 gaugings were carried out in 1930-1932. These were used to construct a rating curve, which they believed could be fairly permanent; there is in fact a protruding rock bar at the site (Sutcliffe and Parks 1999). The rating of the Jur River at Wau station is $Q = 49.14(h-9.64)^{1.646}$ in m^3/s.

3.7.3 River Sobat Basin

3.7.3.1 General

The Sobat contributes about half the flow of the White Nile and about a sixth of the whole Nile; its flow is therefore almost equal to the outflow from the Sudd (Sutcliffe and Parks 1999). The basin derives most of its runoff from the Ethiopian mountains and in the absence of lake storage provides the seasonal element to the flows of the White Nile. It also receives occasional contributions from the Pibor which drains a wide area to the south. During years of heavy rainfall on the Baro and other Ethiopian tributaries, high flows are spilled from the river system to the Machar marshes and other wetlands. For this reason the river was studied for one of the early water-saving or conservation schemes to reduce evaporation losses in these wetlands.

However, the hydrology of the basin is relatively little known as the river straddles the border between Sudan and Ethiopia, and access has not been easy to determine the flows at key points of the river network and in particular the spills from the main rivers into adjoining wetlands.

3.7.3.2 Hydrology of Sobat sub-basin

The major wetland within the Sobat basin, the Machar marshes, is little known, but its hydrology may be indicated by comparing flow records at sites down the Baro and Sobat (Sutcliffe and Parks 1999). A major source of inflow to the marshes is channel flow and over bank spill from the Baro, and this spill is illustrated by flows along the Baro. The flows of the upper Baro have been measured at Gambeila. Levels have been measured since 1905 but no flows calculated until 1928. This relation [$Q- 100(h-8.77)^{1.54}$ in m3 /s] has now been used to convert 10-day levels to flows for 1905-1927, which extend the record from 1928 to 1959 both levels and discharges were measured regularly and flows were calculated from gaugings during each year. The flows of the Baro at its mouth, above the Pibor junction, were measured almost daily in 1929-1933, and then about twice a month from June to December in 1941-1962, when gaugings became less frequent.

The overall losses on the Baro system may also be illustrated from annual flows at Gambeila and the Baro mouth. An increase in flow has little effect downstream. However, the complex pattern of spilling, with outflows and return inflows through channels, can be deduced by direct measurement or by measuring flows upstream and downstream of each junction. Over bank spilling also occurs over both banks and can only be estimated using successive measurements and observation of the proportion of spill over each bank (Sutcliffe and Parks 1999).

3.7.3.3 Geography of the Sobat basin

The Sobat flows to the White Nile from the confluence of its two major tributaries: the Baro and the Pibor (Sutcliffe and Parks 1999). The Baro (41 400 km2) drains an area of the Ethiopian mountains east of Gambeila rising to a peak of 3300 m. The Pibor (109 000 km2) receives the Gila and Akobo from the mountains south of the Baro basin, but also drains a wide area of the plains east of the Bahr el Jebel, from which there is little runoff in most years but high flows in some years. The mountain catchment is largely thickly wooded, with vegetation ranging from thorny savannah to thick tropical forest. On the plains at the foot of the hills the woodland gives way to the west to open grassland, which is swampy in the rains but nearly waterless in the dry season (Hurst & Phillips, 1931).The upper Baro above Gambeila (23 500 km2) collects a number of mountain streams descending from the Ethiopian plateau through deep gorges. Below Gambeila it flows west towards the Pibor junction through a tree-bordered channel which emerges into a grass dominated area. About 100 km above the junction it splits into the Adura and the Baro which rejoin 70 km downstream; the Baro receives the Jokau tributary but several spill channels to the north connect the river with the Machar marshes and at high flows the river is also liable to overtop its banks and inundate large areas. Below the Baro-Pibor confluence the Sobat follows a winding course about 100-200 m wide through alluvial banks in a grass plain, with adjacent grass swamps. Several small seasonal water courses, like the Khor Nyanding and Khor Fullus, join the river from the south; the Sobat catchment is about 36 800 km2.

The climate of the Sobat basin varies greatly between the Ethiopian mountains and the plain. The rainfall of the upper Baro basin ranges from 1300 mm at Gambeila to 2370 mm at Gore, between April and October, with a tendency towards two rainfall seasons evident in individual years. The Pibor basin has lower rainfall, with an average of about 950 mm over the same months, but the rainfall on the plain is only about 800 mm.

3.8 Jonglei canal

The average annual While Nile inflow and outflow of the Sudd has being estimated as 49 and 21 BMC/year, respectively for period 1961-1983 (Mohammed 2005). The difference of inflow and outflow is losses as evaporations (28 BMC/year), this huge amount of evaporation depletion has attracted water resources planners to build short cut channels for bypassing the river water. The Jonglei channel phase 1 is the first phase in a series of proposed water conservation projects. The canal is 360 km long, 2/3 of work is completed, has an average bed width of 38 m and depth of 4 to 8 m, with ground slope varies between 7 to 12 cm/km. if water of the white Nile at diversion site in Bor Town flow into Jonglei canal before spill into Swamp area, the Sudd swamp flooding area will be reduced approximately about 30%.

CHAPTER FOUR

4. Materials and Methods

4.1 General

The methodologies and materials used in this study to achieve the objectives of the research are given in this section. Is as shown in fig 4.1 below:

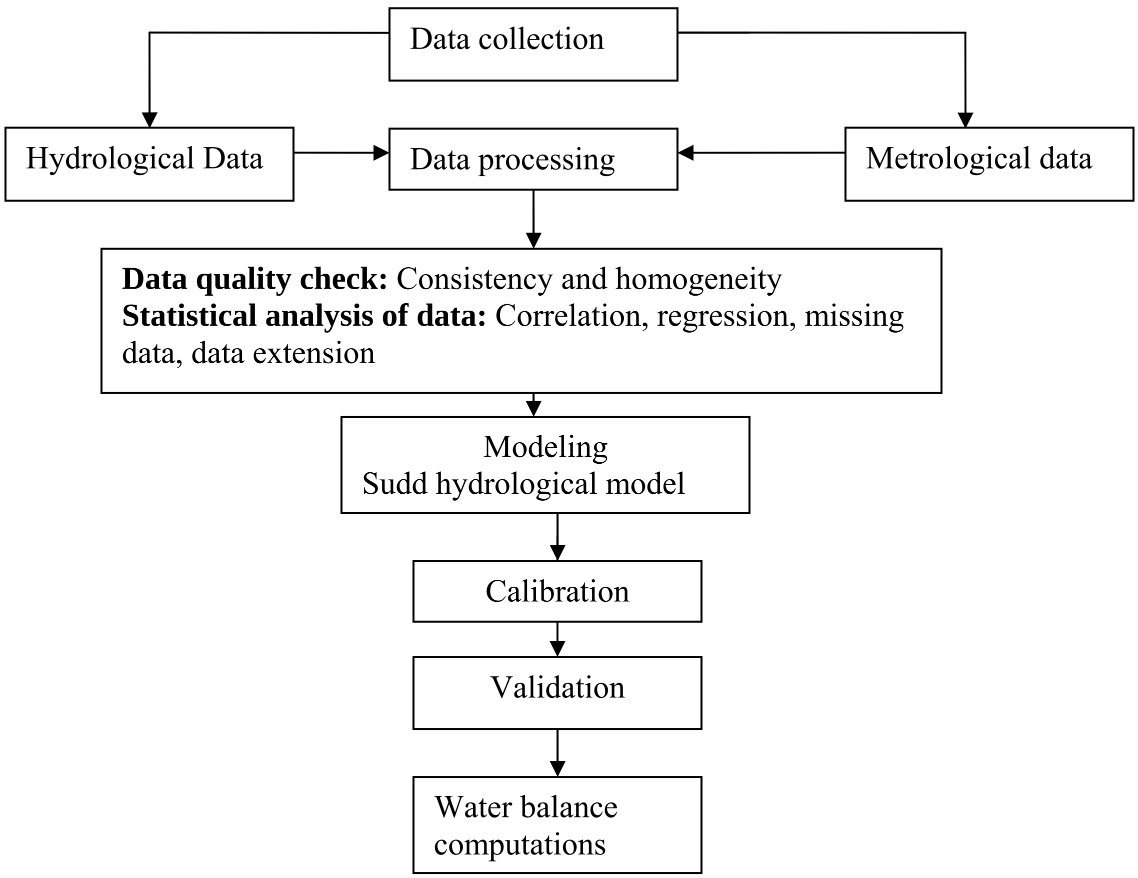

Figure4. 1: Schematic representation of the research general procedures.

4.2: Data collection

Collection of the relevant secondary data from all available sources was made i.e. hydro-meteorological data (rainfall, temperature, relative humidity, river discharge,) from respective offices of government agencies in Khartoum as Sudan Meteorological Authorities, Ministry of irrigation and water resources an, and also from previous studies. Most of the data are available in hard copies.

The Digital Elevation Models for the whole Africa continent of 30*30 m resolution have been taken from Sudan remote sensing authorities Data Base. The DEM data was used to delineate the major sub catchment of South Sudan river basin in Arc GIS-SWAT software.

4.3 Data processing

4.3.1 Checking the data quality

4.3.1.1 Homogeneity

In order to find similar regions monthly rainfall values were non-dimensional and plotted to compare the stations with each others. The non- dimensional of the monthly value carried out by:

$$P_i = 100\ \%(P_{vi}/P) \qquad 4.1$$

Where P_i = non-dimensional value of precipitation for month i

P_{vi} = Over years averaged monthly precipitation of the station i

P = the over years average yearly precipitation of the station

4.3.1.2 Consistency

If the conditions relevant to the recording of a raingauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of the station. This inconsistency would be felt from the time the significant change took place. Some of common causes for inconsistency of record are: i- shifting of raingauge station to a new location, ii- the neighborhood of the station undergoing a marked change iii- change in the ecosystem due to calamities, such as forest fires, land slides, and iv- occurrence of observational error from certain date. The checking for inconsistency of record is done by the double – mass curve technique. This technique is based on the principle that when each recorded data comes from the same parent population, they are consistent (Subramanya, 2006).

4.3.2 Filling and extension of data

Some times, the rainfall amounts or discharge measured at a certain gauges for a certain months may be missing due to the absence of some observer or instrumental failures, stop operation of stations for long period due to political problem or security problem in the areas. In such causes, it is needed to estimate the missing data amount by approximating the value from the data of the nearby gauging stations and homogenous stations**.** The precipitation value missing at a site can be estimated from concurrent observations at three or more neighboring stations and homogenous stations, known as index stations, located as close to and evenly spaced from the missing data stations as possible. For the river flow missing data can also be estimated with near by station in same river course in downstream or upstream of the river.

As it was mentioned earlier, the record measurement was stopped since 1983 for the stations in south of Malakal due to insecurity in area. For this reason, it required to have a way to extend those records. Numbers of literatures describing and reviewing the methods that are using in hydrology to extent the missing data records are available. The double –mass curve method, Correlation with catchment areas and regression analysis between the flows at base and index station, are described by (Ojha, *et al.,* 2008). In this study, the method of simple linear regression analysis between the flows is adopted for the reason that there is no detail information for the catchment, and the method can extend monthly records. The method is adopted only to extend the data record of Hilleit Dolleib and Lake No stations. The method has also been widely used and successfully applied for extension of the flow data record , (Nawaz and Khan, 2006) are Extended the Flow Records at Warsak station on Kabul River in Pakistan ,(Aregahegn, 2003) has use the regression method and other methods to extended flow record for some catchments in Ethiopia .

.If Qs is dependent variable and Qz is independent variable, then:

$$Qs = a + bQz \qquad 4.2$$

Where Q_s = river flow at station (s) (m^3/s)

Q_z = river flow at station (z) (m3/s)

And, a and b are regression coefficients and can be obtained by using linear regression analysis.

$$b = \sum_{i=1}^{n} (Q_{si} - \overline{Q}_s)(Q_{zi} - \overline{Q}_z) / (\sum_{i=1}^{n} (Q_{si} - \overline{Q}_s)^2) \quad 4.3$$

$$a = \overline{Q}_s - b\overline{Q}_z \quad 4.4$$

$$\overline{Q}_z = \frac{\sum_{i=1}^{N} Q_{zi}}{N} \text{, and } \overline{Q}_s = \frac{\sum_{i=1}^{N} Q_{si}}{N} . \quad 4.5$$

From above three equations:

Q_{si} is flow at station s in month i

Q_{zi} is flow at station z in month i

$\overline{Q}_s and \overline{Q}_z$ Are mean of flows and stations s and z respectively

The nonlinear regression technique is employed, with multiple linear relationship reached until lag of 10 months, the method has be descript by (Ojha, Berndtsson and Bhunya 2008).and is expressed as: $Q_{ti} = a + bQ_{tj} + cQ_{j(t-1)} + ----$ + Error 4.6

Where: Q_{ti} = flow in t^{th} months at station i

Q_{tj} = flow in tth months at station j (available records)

$Q_{j(t-1)}$ = flow in (t-1)th month at station j

a = constant (always a negative quantity to account for the initial losses)

b an c = are constants which are less than one .

4.4 Sudd water balance model

In order to understand the basic hydrological process, water balance computation of the Sudd swamp area is made using excel spread sheet. The area was treated as a simple reservoir, and the volumes and areas of flooding were estimated for the period 1950-2009.

4.4.1 Hydrological model background

The inflow to the swamps combines the damped outflow from the East African lakes, which respond slowly to periods of high and low rainfall, and the seasonal and variable flows of the rain-fed torrents above Mongalla.

Below Mongalla the channel capacities are less than the flood flows and the alluvial channels themselves are above the flood plain. The excess flows during the peak flow leave the river through spill channels and inundate wide areas on both sides of the river banks. The flooding pattern is complex but may be described by a water balance model, where the swamp storage is represented by a reservoir. A detailed study of a surveyed sample reaches between Juba and Bor (Sutcliffe, 1974) has shown that it is possible, given inflow and outflow records, to reconstruct volumes and levels of flooding over a number of years. In order to develop a simple hydrological model to monitor the behavior of the Sudd over the historical period, inflow and outflow records are required together with estimates of rainfall and evaporation.

4.4.2 Description of the model

The study of the water balance is the application in hydrology of the principle of conservation of mass, often referred to as the continuity equation. This states that, for any arbitrary volume and during any period of time, the difference between total input and output will be balanced by the change of water storage with in the volume.

The water balance model used in this study is similar to that was developed by Sutcliffe, 1974.The model inputs are river inflows and outflows from an area of Sudd swamp plus rainfall, and evaporation. In this model the main assumption, is the sudd swamp can be treated as a reservoir whose storage volume is cumulative inflow less outflow (Sutcliffe, 1974). To estimate direct rainfall and evaporation volumes for this reservoir, the area flooded for a given volume of storage is required; this corresponds to the area-capacity curve of the reservoir. The equation of continuity for a time interval δt is:

$$\delta V = [Q - q]\delta t + A(R - E) - r\delta A \qquad 4.7$$

Where dV is change in volume of flooding (MCM)

Q is the river inflow into Sudd (MCM/month)

q is river outflow from Sudd (MCM/month)

R is amount of rainfall over Sudd area (mm/month)

E is amount of water evaporate over Sudd area (mm/month)

A is flooded area (Million m^2)

r is soil moisture recharge (MCM/month)

δA is change in flooding area (Million m^2)

δt is time interval and has be taken as a month

To made the equation (4.7) dimensional homogeneity all units are convert to the meters.

The inflows and outflows, Q and q, are known for the period 1950-2009, the rainfall depths, R, are known, and the evaporation, E, may be taken as the mean open water evaporation and estimate by using Thranthwate method . The soil moisture recharge, r, may be estimated as 200 mm at the beginning of the wet season, and decreased by ∑(R - E) to allow for preceding months when rainfall exceeded evaporation.

Thus the series of records provides for each month an equation in which, given the initial values of area, A, and volume, V, there are two unknowns, δA and δV. Moreover, there must exist a relationship between storage volume and flooded area which may be expressed as: A = f(V).

This relationship could be determined only by detailed topographical survey over the whole area, but it is possible to deduce and test a reasonable form of such a relationship. In three reaches where survey and hydrological records exist on the White Nile and the Bahr el Jebel (Sutcliffe, 1957), the relationship between area and volume of flooding can be deduced and in each case is linear within the range of information. Although the evidence is from the fringes of the swamp, it seems reasonable to use a linear relationship for the whole Sudd and to express it as A = kV bearing in mind that V = 0 when A = 0. The relationship A = kV leads to expressions for V and A in terms of level, h, of the form (Sutcliffe, 1957):

$$V = a * e^{kh} \qquad 4.8$$

$$A = k * a * e^{kh} \qquad 4.9$$

Starting the analysis at the beginning of month i, with an initial storage, V_i, and area, $A_i = kV_i$, and taking the net evaporation as $(E - R)A_i$ over the initial area, the equation of continuity leads to:

$$\begin{aligned} V_{i+1} &= V_i + Q_i - q_i - A_i(E_i - R_i) - r(A_{i+1} - A_i) \\ &= V_i + Q_i - q_i - kV_i(E_i - R_i) - rk(V_{i+1} - V_i) \end{aligned} \qquad 4.10$$

$$V_{i+1}(1 + rk) = V_i(1 + rk) + Q_i - q_i - kV_i(E_i - R_i)$$

Where Q_i, qi, E_i and R_i, are tabulated and r varies with net rainfall from an initial value of 0.2 m. This equation provides an initial estimate of V_{i+1} and thus A_{i+1}. Because the evaporating surface is strictly the mean of the initial and final values for the month, these estimates were used to adjust the evaporation estimate to the mean flooded area to give:

$$\left(\frac{A_{i+1} + A_i}{2}\right)(E_i - R_i) \qquad 4.11$$

In a second iteration, this was considered sufficient.

4.4.3 Model components

River flows

The river flows required are the inflows at Mongalla, where the Bahr el Jebel flows in a single channel plus torrents inflow and the outflows from the tail of the swamps, deduced from the differences between the White Nile at Malakal and the Sobat at Hillet Doleib. These flows are available from 1912 to 2009 for Malakal and from 1912 to 1982 for Mongalla and Hillet Dollieb and torrents inflow estimate from 1960-1980. The flow from the Bahr el Ghazal at Lake No was not taken into account, as most of this is spill from the Bahr el Jebel (Sutcliffe and Parks 1987).

Rainfall

Six rainfall stations near the Sudd swamp are available for different periods,: Bor, Fangak and Bentiu stations inside the swamp area while the Malakal, Juba and Yei outside the swamp area. The aerial rainfall over Sudd was estimated using Thiessen Polygon method. In this method, the weight is assigned to each station in proportion to its representative area defined by a polygon. It is assumed that the entire area with in a polygon is nearer to the rainfall station that is included in the polygon than to any other rainfall station.

Evaporation

Evaporation is considered from two aspects: evaporation from an open water surface and evapo-transpiration, which is the evaporation of intercepted water and transpiration from vegetation. Knowledge of evaporation is a major importance in water resources assessment among others to determine the amount of water lost through the process of evaporation in the water balance computations of land, rivers, lakes and reservoirs.

The evaporation was estimate using throanthwaite and Hamon methods. The methods were selected for the reason of availability of the data; the only metrological data available are the temperature, from Juba station out side the swamp area, also the assumption of take potential evaporation as actual evaporation led to chows the methods. The adjustment was made for method; by adjust the constant (c) from 1.6 to 2 Base on criteria of variation of this constant from place to place (it is low in cold area and high in hot one), the adjustment was done by comparison the estimate evaporation with pervious estimation.

Torrent inflow

The Bahr el Jebel is the most complex of the Nile reaches as it receives inflows from a number of seasonal torrents which are not measured directly; but there some methods of estimating the torrent flows, described in Sutcliffe and Parks, 1999 which are based on a comparison of dry season Mongalla flows and Lake Albert levels to estimate the lake outflows. The lake outflows reach their maximum in October-December, after the peak of the torrent flows. Approximate torrent flows were deduced and published in The Nile Basin, vol. V and subsequent supplements to vol. IV. Includes these estimated torrent inflows for the periods 1907-1960 and 1961-1980, excluding the dubious value for 1964.

These available torrents inflow from 1960 to 1990 are used and employed in the model as inflow in to swamp area , the extension for records has done up to 2009 using the simple regression between torrents inflow and rainfall over area , the result was quite reasonable , with $R^2 = 0.7038$.

Flooded areas

The areas flooded on specific dates can be used to test the model. Areas cannot be measured directly but can be estimated from air photography, satellite imagery or indirectly from vegetation maps. Measurements were found for four separate dates. Maps based on air photography in 1930-1931 were plan metered to give a mean flooded area of 8300 km^2 at that period; a map based on satellite imagery of February 1973 gave a flooded area of 22 000 km^2 on that date, reflecting the increased Mongalla flows after 1961. The areas of permanent and seasonal swamp may be deduced from vegetation, which responds to flooding over a few years. A vegetation map based on aerial survey, satellite imagery of 1979-1980 and field observation gave estimates of permanent swamp of 16 600 km and seasonal swamp of 14 000 km^2. A map based on reconnaissance in 1950-1952 (Jonglei Investigation Team, 1954,) gave permanent swamp of 2800 km and seasonal swamp of 11 200 km2; the permanent swamp was probably underestimated by comparison with the seasonal swamp.

Sudd inflow and outflow correlation

The analysis has been based on measured outflows as well as inflows. It is necessary to adopt the model to predict what the effects of the inflow at Mongalla on the outflow at Malakal.

Inflows at Mongalla and outflows at the tail of the swamps were correlated with various lags and in both linear and logarithmic form, using records from 1912-1980. The variance explained increased from 49.59 to 55.95% as the lag was increased to three months.

The equation of the lag three months was selected to predict outflows from inflows with a three month lag. However, this equation implies that outflow, q, exceeds inflow, Q, at low flows, whereas q→ Q as Q → 0, A simple equation with these properties is (Sutcliffe and Parks, 1999):

$$q_t = Q_{t-3} - c(Q_{t-3})^2 \qquad 4.12$$

And the value of c can be derived to fit the prediction equation without discontinuity of gradient:

$$q_t = Q_{t-3} - 0.000214(Q_{t-3})^2 \qquad \text{For Q < 1730 in MCM/MON} \qquad 4.13$$

$$q_t = 33.615(Q_{t-3})^{0.4872} \qquad \text{For Q > 1730} \qquad 4.14$$

The above two Equations were used with Mongalla inflows to predict lagged outflows for the period 1950-2009, and these outflows were used in the reservoir model to provide a second series of estimated areas of flooding.

4.4.4 Modeling procedures

The step by step procedures for the Sudd hydrological model can be described as:

1- Assume initial volume (V_i) of the Sudd volume based on the previous study with the reasonable assumption.

2- Compute the initial area A_i of Sudd by multiplying the initial volumes V_i with depth inverse (1/k)

3- Calculate the initial loss by using the initial area (A_i) of Sudd = A_i (P_i – PET_i)

4- Calculate change in the storage volume as following:

$$\Delta V_i = Q_t + Q_{tl} + A_i\left(P_i - PET_i\right) - q_t$$

$q_t = Q_{t-3} - 0.000214\left(Q_{t-3}\right)^2$ For Q < 1730 and $q_t = 33.615\left(Q_{t-3}\right)^{0.4872}$ For Q > 1730

Where Q is the inflow whereas the outflow from Sudd is exceeds to inflow (Sutcliffe and Parks 1987).For more details see the previous section in this document.

The above change in volume is not including the soil recharge, which will be calculated in next step.

5- Calculation of the volume by using previous calculated volume and soil recharge volume:

$\Delta V = \dfrac{\Delta V_i}{1 + r * k}$ If the ΔV_i >0, otherwise $\Delta V = \Delta V_i$

6- Calculation the total change in storage volume by sum the above two calculated volume in steps 4 and 5.

7- Estimate the area by multiplying the total volumes by the depth inverse.

8- Use the new estimate area to calculate the evaporation losses.

9- Calculate the change in volume by using the new estimate losses. And this volume was used in the next second iteration.

10- Calculate the soil recharge by considering the area of the Sudd swamps shrinks and swells during the season. : Recharge = r*k*ΔV.

11- Estimate the outflow from Sudd area,

$q_t = Q_{t-3} - 0.000214\left(Q_{t-3}\right)^2$ For Q < 1730 in MCM/MON

$q_t = 33.615\left(Q_{t-3}\right)^{0.4872}$ For Q > 1730

12- Repeat the whole procedures until the end of the period.

4.4.5 Model Efficiency

Relative error(RE) of volumetric fit between simulated and observed; Nash and Sutcliffe efficiency criteria(R^2) Nash and *Sutcliffe* (1970) and Bias $(B)$are used to check the model efficiency. The RE given by:

$$RE = \frac{\sum (R_g - R_P)}{\sum R_g}.100\% \qquad 4.15$$

Where R_g : gauged (observed) data and R_p : Simulated runoff

The value of RE is close to zero for good simulation.

The Bias, $B = \frac{\sum (R_g - R_P)}{N}$

The Nash and Sutcliffe efficiency criterion is given by R^2as:

$$R^2 = \frac{F_0 - F}{F_0} \text{X } 100\% \qquad 4.16$$

Where: $F_0 = \sum (R_g - R_{av})^2$, $F = \sum (R_g - R_p)^2$, and $R_{av} = \frac{\sum (R_g)}{N}$

Where R_{av} : Average of the observed runoff

N : Record length

F_0 : is the sum of square of deviation of observed runoff from the mean

F : is the sum of squared deviation between observed and predicated Runoff

Minimization of F ,in another words a value of close to 0 and R^2 near 100% is a criterion that can describe the performance of a good model, and the corresponding point good model parameters can be obtained. This can be described in another form.

$$F = \min \sum \left[R_g - R_P(X_t; \beta) \right]^2 \qquad 4.17$$

Solving the minimization problem of above equation furnishes estimates of model parameters, β for the input parameters X_t, in this case values of r, k with P, PET respectively.

4.5 Estimation of the potential Evaporation

Accurate estimation of evaporation is vital for estimation and quantifies the hydrological components in water balance equations. In this study the monthly time scale and temperature base methods was adopted for both reservoir and catchment evaporation estimation (open water evaporation). The three temperature methods employed are: Thronthwait method, Hamon method and Cropwater model, from those three the earlier two are apply in Sudd water balance model to estimated the inundation area .that due to lack of the data .

4.5.1 Correlation of monthly estimates between methods

The monthly evaporation values computed using the different methods were analyzed to correlate with Panmenn evaporation using a linear regression equation:

$$Y = mX + c \qquad 4.18$$

Where Y represents evaporation from Penman and X is the ET estimated from the above-mentioned methods, and m and c are constants representing the slope and intercept respectively. This was used to compare of the two methods with FAO recommended method of Panmenn.

4.6 Estimation of Areial Rainfall

Precipitation intensity can vary greatly during short periods of time and from one place to another. Consequently, it is difficult to get an areal estimate of precipitation if the number of gauges in an area is small. The problem according to the above is to calculate areal precipitation values based on the point measurements that the gauges represent. The collection area of the gauge is very small as compared to the area that the gauge is supposed to represent. Therefore, some technique is needed to generalize the point measurements to areal estimates to be valid for. The areal estimates of rainfall are needed in order to be able to calculate water balance for the catchments.

The areal precipitation is computed from the record of rain gages with in the area by the following methods: 1- Arithmetic or station average method 2- Weighted average method. (Thiessen polygon method / Isohyetal method)

The thiessen polygon it used in this study and can be expressed as:

$$P_m(t) = \frac{\sum P_i(t) A_i}{A} \qquad 4.19$$

Where A = Total area, and Ai = particular area related to gauged i with rainfall P_i.

CHAPTER FIVE

5. HYDROLOGICAL AND METROLOGICAL DATA ANALYSIS

5.1 Hydrological Data

Political problems in the southern Sudan prevented the network from being reinstated completely, though several records for the Bahr el Ghazal tributaries were maintained by the Sudan authorities in the 1970s (Sutcliffe and Parks 1999). Since about 1983 measurements have not been carried out south of Malakal. The key gauging stations at Upper White Nile at south Sudan are: Malakal station (on white Nile) , Wau station (on Jur River) Bahr el Ghazal sub-basin , Lake No – outlet of Bahr el Ghazal sub-basin , Mongalla station on Bahr El Jebel River and Hellit Dolleib on Sobat River .

All the above station records are used in this document, and are discussed in detail in this chapter.

Table5. 1: Hydrological data

Station	Sub-basin	Location		Available record	Missing period	Sources of data
		Lat degree	Lon degree			
Malakal	While Nile	9.58	31.62	1912 - 2009	No missing	From 1912 -1996 from PJTC – Khartoum office & 1997-2009 from GONU-MOIWR
Lake No	Bahr el Ghazal	9.3	30.28	1912-1980	30 year	From PJTC – Khartoum office
Mongalla	Bahr el Jebel	5.20	31.77	1912-1985 2005-2009	20 year	1912-198 from PJTC – Khartoum office 2005-2009 DIU
H-Dolleib	Sobat			1912-1983	27 year	From PJTC – Khartoum office
Wau	Jur Bahr el Ghazal			2000-2006	-	Hydrology department – Wau office.
Gambelia	Baro-Akobo	8.15	34.35	1967-2004	-	Ministry of Water Resources – Ethiopia – Addis Ababa
Pugnido	Baro-Akobo	-	-	1977-1989	-	Ministry of Water Resources – Ethiopia – Addis Ababa

(PJTC = Permanent Joint Technical Commission and DIU = Dams implement Unit).

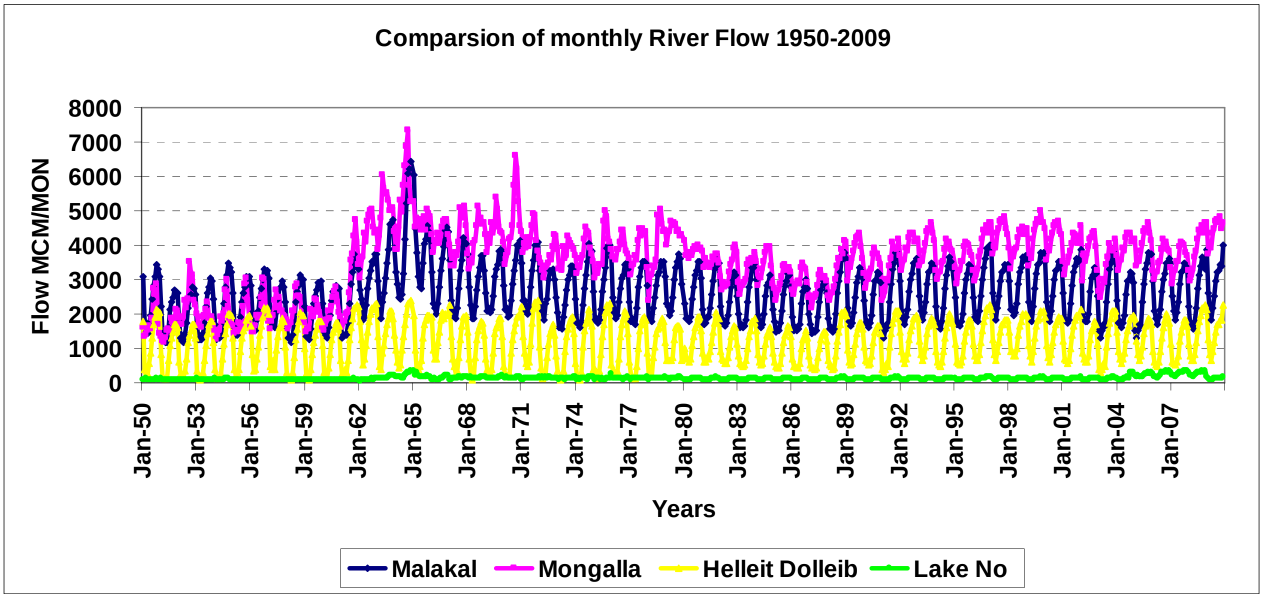

Figure5. 1: Discharges at main gauge stations.

The time series of monthly discharge at four main gauge stations is shown in figure (fig 5.1). The flow at four stations is increased after period of 1963 at stations Malakal, Mongalla and Lake No, while the Hilleit Dolleib is fairly constant, it is also clear from the figure that the Lake No flow is also affected by Bahr el Jebel spills during the flow rise of Lake Victoria in 1963 – 1966. It is showing the rise in the level and volume of water comes from Lake Victoria outflow.

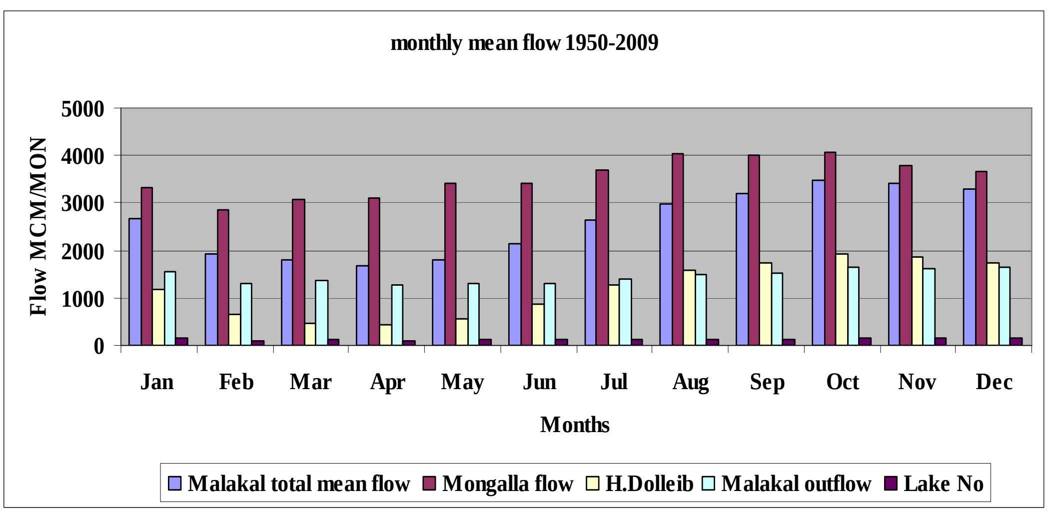

Figure5. 2: The comparison of the flow at stations

The comparison of the discharge for the stations shows the highest discharge is measured at Mongalla station between August to October; Malakal outflow is nearly equal to the Hillit Dolleib, while the lowest discharges are found from Lake No stations.

5.1.1 Gauge Stations

Malakal

The Malakal gauge station at Malakal town is used for measuring the flow and stages of the while Nile. The outflows from the Sudd have been measured directly, but the only long-term flow record is derived from the difference between the flows of the White Nile at Malakal and the Sobat at Doleib Hill near its mouth. Measurements at Malakal have been regular since 1906, and have continued to the present. The record of Malakal station has been use in this study to extend the others records from another station.

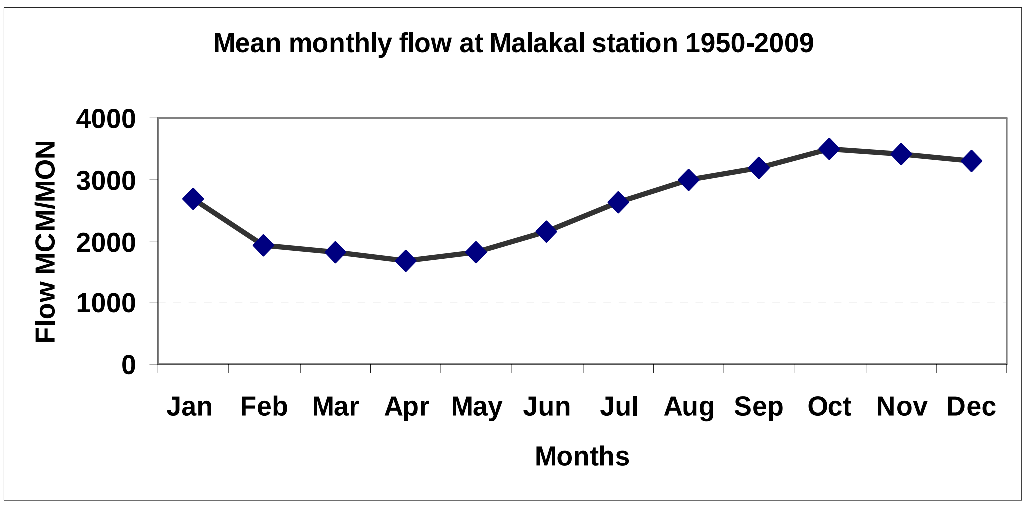

Figure5. 3: Mean monthly White Nile flow at Malakal

On the average (using the data from 1950-2009 years) on monthly basis, maximum flows occurs in October with a minor secondary peak in January and minimum flows between March and May. The total annual flow of the While Nile at Malakal is 31062 MCM/yr.

As it can be observed from the hydrograph of the White Nile River, discharge at Malakal town that The River has no dry out all the years, which mean the river is flowing through out the year, and it can be said that the base flow of the river not dry out during the severe dry years which is possible to depend on runoff of the river throughout the year for irrigation and domestic water supply.

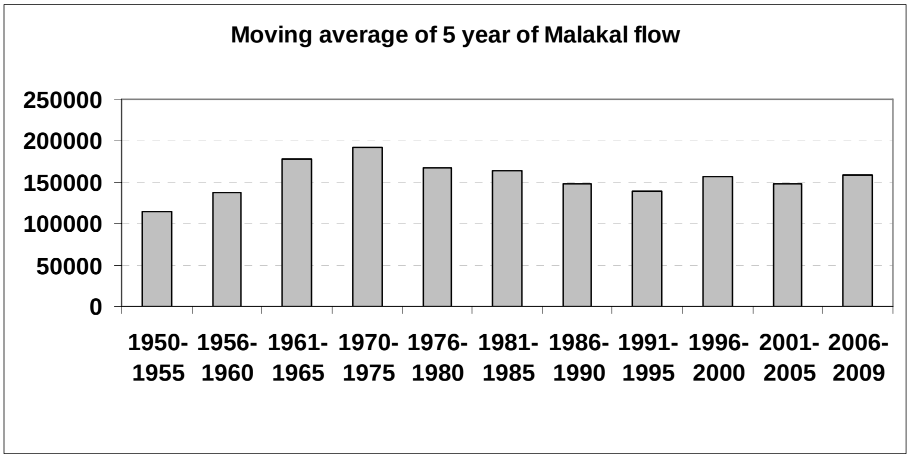

Figure5. 4: 5 years moving average of Malakal station

Moving 5 years average, the discharge of the White Nile at Malakal increasing continuously for consecutive 40 years and come to the original position after 45 years, and again increase for 15 years. There are low flow years for 10 years and high flow years for the 25 years. Therefore, the High and low flow years of the White Nile discharge varies within 30 years. For the future developments and type of developments to be implemented in this area the season should be taken into consideration as far as there is variation in rainfall from year to years.

Mongalla

The most reliable gauging station below Lake Albert is at Mongalla on the Bahr el Jebel (Sutcliffe and Parks 1999). River gauge levels have been recorded here since 1905, at a site where the river enters the Sudd in a single channel. Gaugings have been made since 1907, and have been frequent in some periods and regular in other periods. The flows at Mongalla have not been measured after 1983, but an indication of the flows since that date can be inferred from the Lake Victoria level or outflow series, the decline has continued fairly steadily, interrupted by rises in 1978-1980 and 1998 and by seasonal variations.

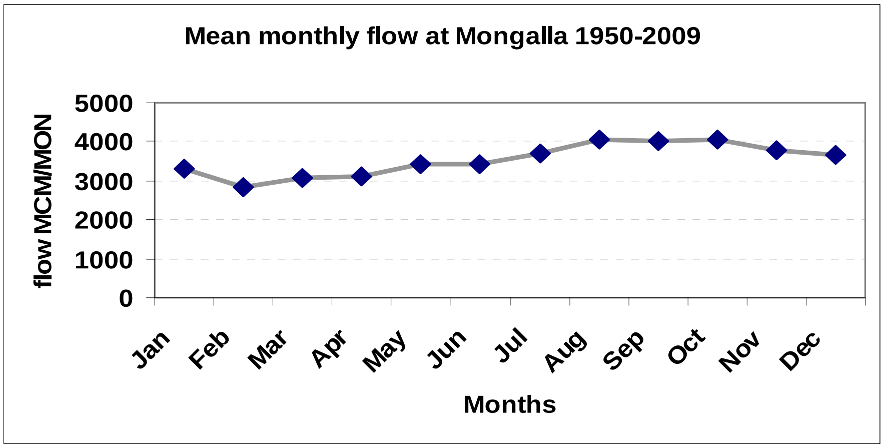

Figure5. 5: Bahr el Jebel flow at Mongalla station

The hydrograph of the Mongalla station on Bahr el Jebel is similar to the While Nile hydrograph at Malakal station during seasons (low and high seasons)

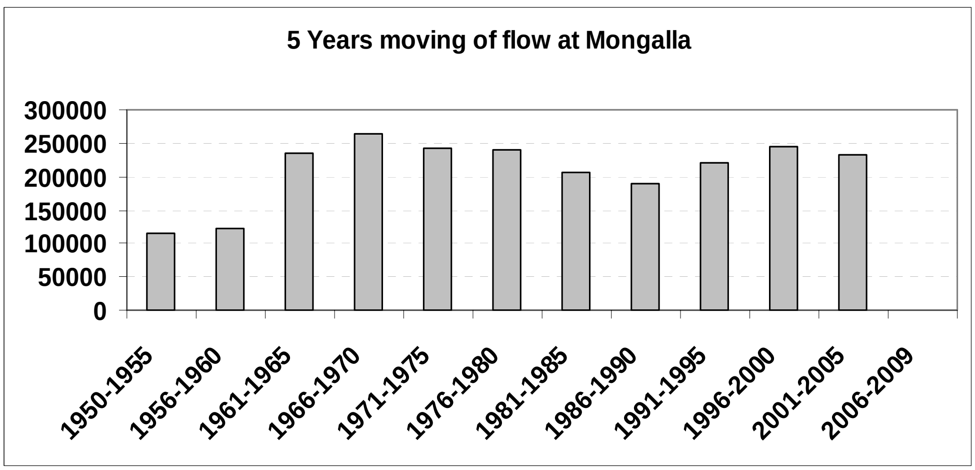

Figure5. 6: Mongalla 5 year moving average

Also the 5 years moving average of the Mongalla station is similar to one of Malakal station

Hillet Dolleib

Gauging at Dolleib Hill or Hillet Dolleib on the Sobat River began in 1906, and continued until 1983 (Sutcliffe and Parks 1999).; the outflows, like the inflows, are not known since 1983. The records at Malakal are reliable, but the Sobat flows are less reliable after the outflows from the Sudd increased in 1964. The Sobat contributes about half the flow of the White Nile and about a sixth of the whole Nile; its flow is therefore almost equal to the outflow from the Sudd.

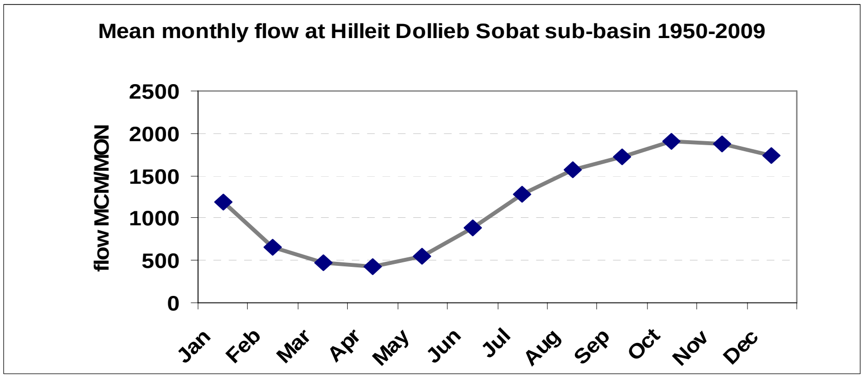

Figure5. 7: Sobat River flow at Hilleit Dolleib

The average monthly of the discharge for period of 1950-2009 of the Sobat River at the Hilleit Dolleib shown the high discharge is on October while the low flow is in the middle of the dry season between April and May. Here there big need to consider the seasons affected of the flow of the Sobat River when it water is to be utilized.

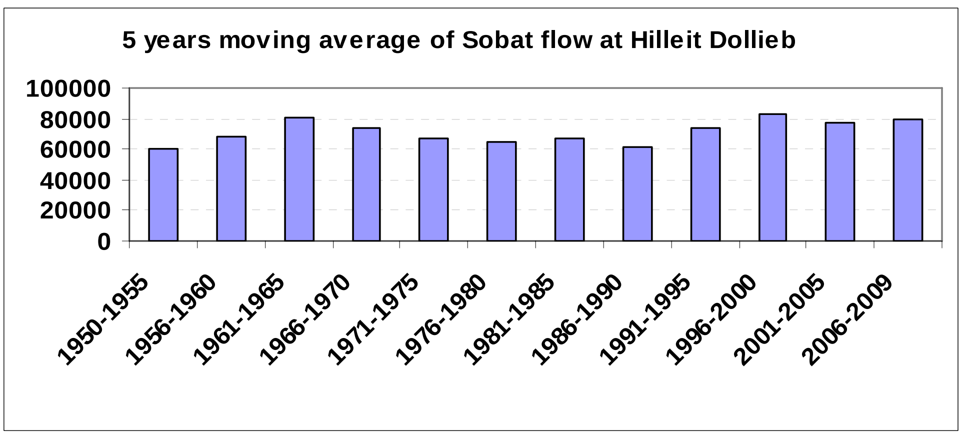

Figure5. 8: 5 year moving average of flow at Hilleit Dolleib

The moving average of flow of Sobat River is showing increasing for 15 years, and decreases for most of 25 years and keeps constant for 15 years.

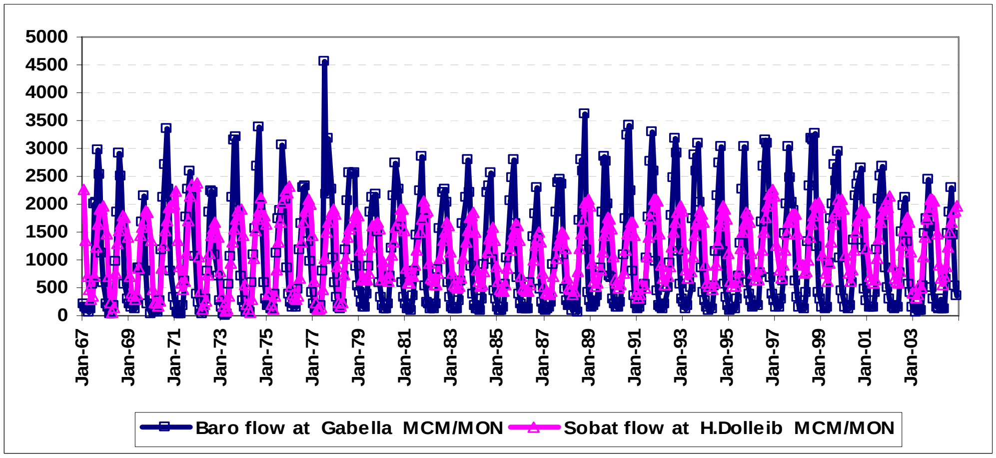

Figure5. 9: Monthly flows at Gambela and Hilleit Dollieb

Figure5. From fig 5.9 the discharge of the Baro River almost dried out during the try seasons in April. In actual sense the discharge at Gambellia town should greater than the discharge at Hilleit Dollieb during the rainy seasons since there are many ephemeral rivers between the two stations which drains the runoff to the river from the catchments of Baro river. However discharge observed at Gambellia station is greater than measurements taken at Hilleit Dollieb throughout the observed years. This is due to the river loss, abstraction, and spills along the stretch of the river and evaporation even during the rainy seasons.

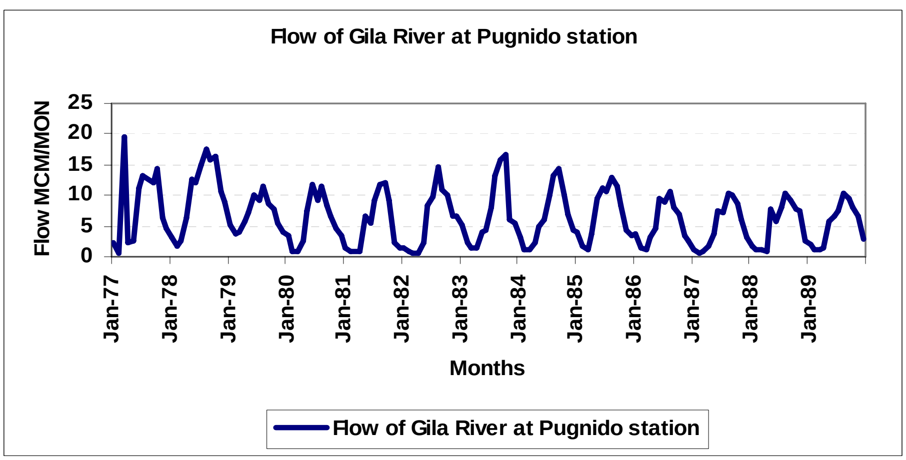

Figure5. 10: Flow of Gila River at Pugnido station as in flow to Sobat basin

The Gila River is one the tributaries of the Baro-Akobo basin in Ethiopia, it join Pibor river at Sudan Ethiopia bounder. The contribution of Gila River flow into Sobat river is small compare with other tributaries as Akobo, Baro and Alwero , as the River is dried out during the dry period , as in the fig 5.10 .

Lake No

At Lake No the Bahr el Jebel turns east and becomes the White Nile, and the Bahr el Ghazal flows into the lake from the west (Sutcliffe and Parks 1999). The Bahr el Ghazal basin is relatively large and has the highest rainfall of any basin within the Sudan. However, the flows of the various tributaries of the Bahr el Ghazal are spilled into seasonal and permanent swamps, and virtually no flow reaches the White Nile. The outflow series has been deduced from the published flows of the Bahr el Ghazal below Khor Doleib, about 40 km above Lake No, where the average annual discharge is only 0.305 Km3 compared with the average inflow of 11.323 km3 . The flows of the Bahr el Ghazal at its confluence with the Bahr el Jebel at Lake No (0.634 km3) are somewhat higher but these appear to include some spill from the Bahr el Jebel just above the confluence (Sutcliffe and Parks 1999).

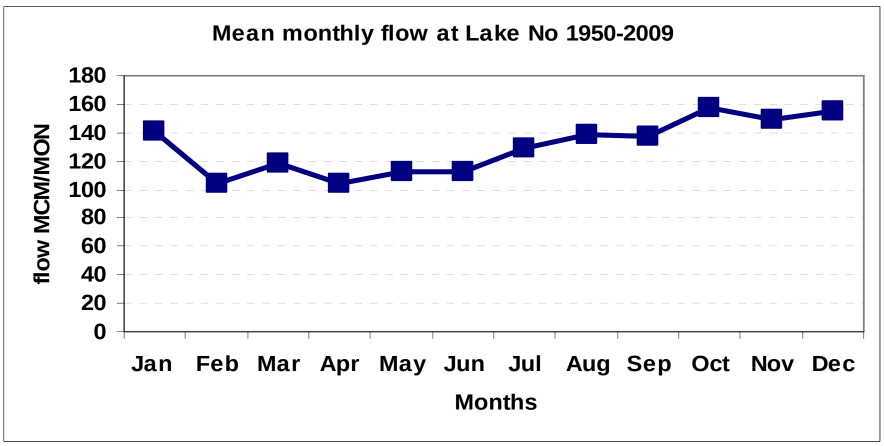

Figure5. 11: Bahr el Ghazal outflow at Lake No

The highest flow at Lake No is on October, which results of the high rainfall fall at up basin of Bahr el Ghazal, because there not any inflow from other nearby catchment into the basin, also the lowest flows occur on the February and April, here also there high peak flow on March in dry season, which is indicted the spill of the Bahr el Jebel.

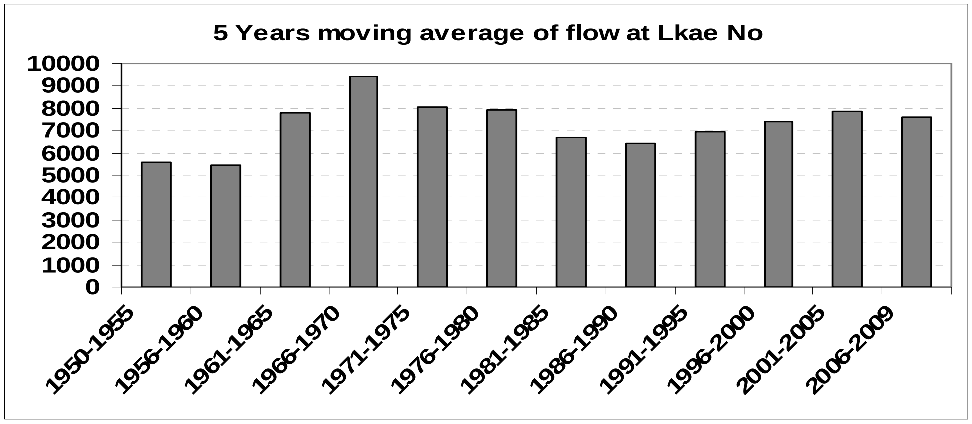

Figure5. 12: 5 year moving average Bahr el Ghazal River at Lake No

The moving average of 5 years for the flow at Lake No, is showing increase for 20 years and than decrease for the 25 years and again increase for 20 years

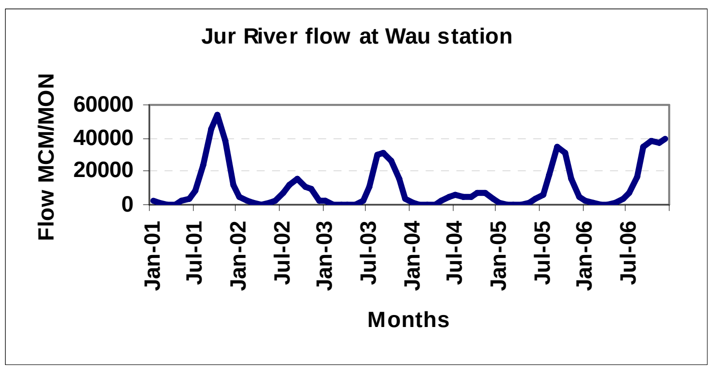

Figure5. 13: flow River Jur at Wau station

From the fig 5.13 the Jur River flow time series from 2001 to 2006 shows that the river is dried out during the try seasons in March, also the highest discharge was in 2006, while the lowest was in 2004. Those discharges are results of the calculation using the rating of $Q = 49.14(h-9.64)^{1.646}$.

5.1.2 Hydrological data records extension

To extend the hydrological data record, the simple linear regression method was adopted for the flow at stations Hilleit Dolleib and Lake No, the results obtained are shown in the table 5.2

Table5. 2: The results of the extension models (Y and X are flows in m3/s)

Parameters	**Hilleit Dollieb station**	**Lake No station**
Equation	Y = 0.7416X-267.74	Y =0.0323X+12.149
Correlation coeff. (r)	0.879	0.624
Coeff. Of deter. (R^2)	0.7755	0.3919
Standard error	For a(SEa) = 46.65 For b(SEb) = 0.05	For a (SEa) = 2.1 For b (SEb) = 0.00203
Confidence interval	For a lower = -358.366 & upper = -175.49 and For b lower = 0.647 & upper = 0.837	For a lower = 7.987& upper = 16.4774 For b lower = 0.028 & upper = 0.036
Test of hypothesis	a = 0 rejected (5.72 >1.96) b = 0 rejected (15.789 >1.96)	a = 0 rejected (5.64>1.96) b = 0 rejected (15.9>1.96)

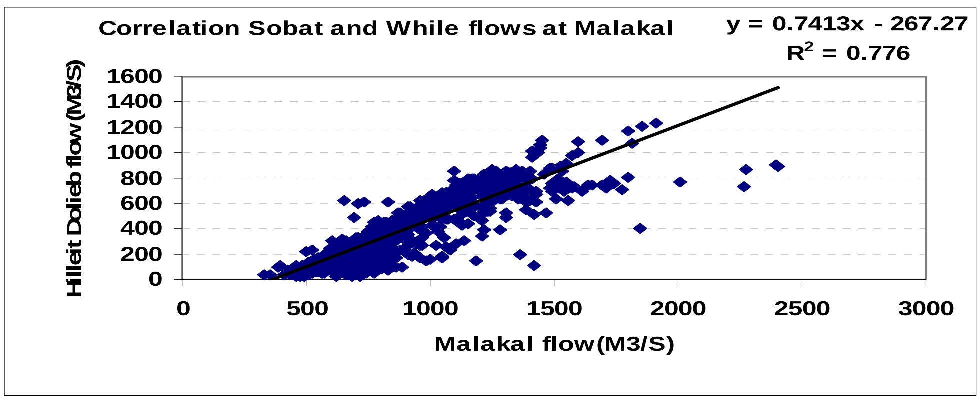

Figure5. 14: Hilleit Dolleib and Malakal linear regression using records from 1912-1982

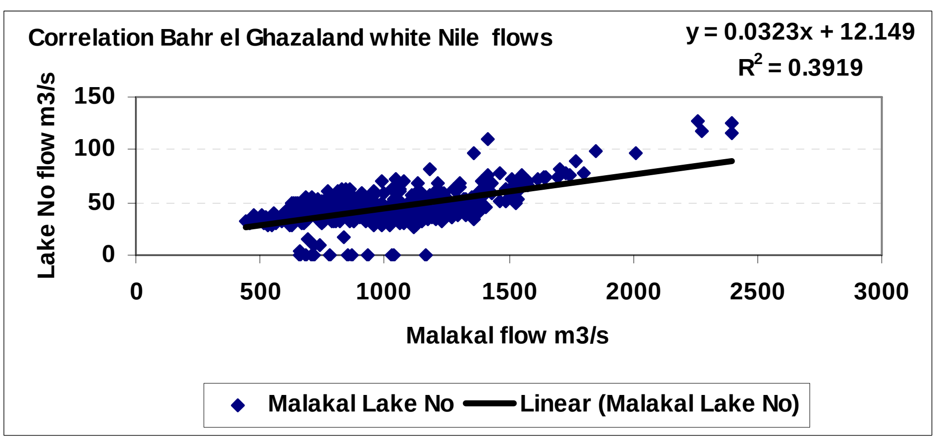

Figure5. 15: Lake No and Malakal linear relationship.

5.2 Rainfall Data Analysis

The rainfall data or weather records data are similar as hydrological data , are not being recorded since 1983 when the civil war breakout in the study area , only long-term record are available for the big town like Malakal , Juba and Wau .

Table5. 3: Rainfall stations and records (Sources for sub-basin area is Mohammed 2004)

Sub-basin	**Area $10^9 m^2$**	**Stations**	**Elevation m a.s.l**	**Location In degree**		**Available records**	**Sources**
				Long (E)	**Lat (N)**		
Bahr el Jebel	38.6	Juba	457	31.36	4.52	1901-2009	FAOCLIM 1901-1996 SMA f1997-2009
		Bor	420	31.33	6.12	1906-1984	FAOCLIM 1901-1996
		Bentiu	389	29.50	9.14	1950-1984	FAOCLIM 1901-1996
		Fangak	390	30.48	9.00	1922-1982	FAOCLIM 1901-1996
		Kajo-Kaji	910	31.36	3.54	1916-1982	
		Yei	830	30.40	4.50	1914-1981	FAOCLIM 1901-1996
Bahr el Ghazal	59.27	Wau	438	28.10	7.42	1904-2009	FAOCLIM 1901-1996 SMA f1997-2009
		Tonj	429	28.45	7.17	1950-1981	FAOCLIM
		Aweil	415	27.24	8.46	1932-1984	FAOCLIM
		Raga	545	25.41	8.28	1907-1989	FAOCLIM
		Maridi	749	29.28	4.55	1908-1985	FAOCLIM
		Meshras Er-R	390	29.15	8.24	1907-1963	FAOCLIM
		Rumbek	420	29.42	6.48	1908-1985	FAOCLIM
		Yambio	650	28.24	4.34	1921-1979	FAOCLIM
Sobat	42.9	Torit	625	32.33	4.25	1923-1984	FAOCLIM
		Kapoeta	-	33.24	4.30	1938-1984	FAOCLIM
		Pibor	410	33.8	6.48	1919-1974	FAOCLIM
While Nile	-	Malakal	388	31.39	9.33	1909-2009	FAOCLIM 1901-1996 SMA f1997-2009
		Renk	282	32.47	11.45	1906-1996	
		Melut	385	32.11	10.26	1906-1987	

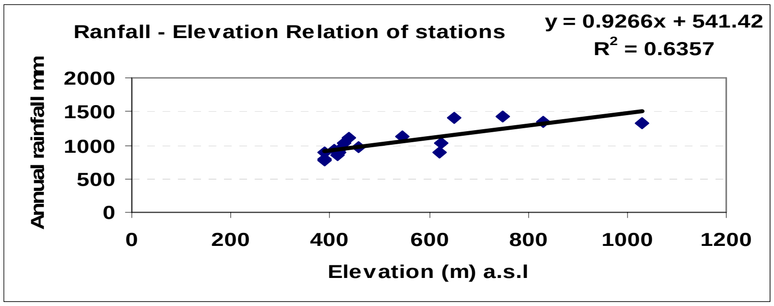

Figure5. 16 : Scatter Plot of Annual Rainfall-Elevation of the Stations

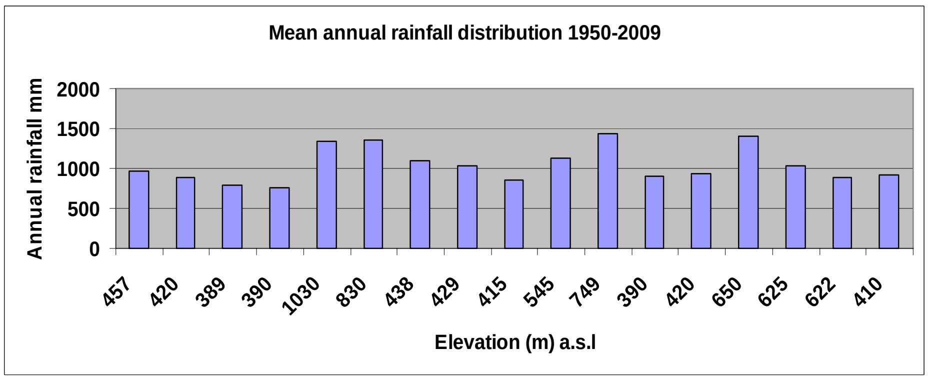

Figure5. 17: Annual Rainfall Distribution – Elevation of the stations elevation

Precipitation in the catchments varies with altitude. High altitude areas like Kajo-Kaji ,Yei,Maridi and Yambio mountains receive mean annual rainfall of over 1350mm while the lowland like swamps areas gets average depth of about 850 mm. However, the correlation coefficient between precipitation and altitude is not very strong due orographic effect and is found to be 0.6357. There is significant orographic effect on the spatial distribution of precipitation over the area. Areas close to mountains of Equatorial highland get higher mean annual precipitation than areas found far away from the mountainous region even if the later ones are in higher altitudes.

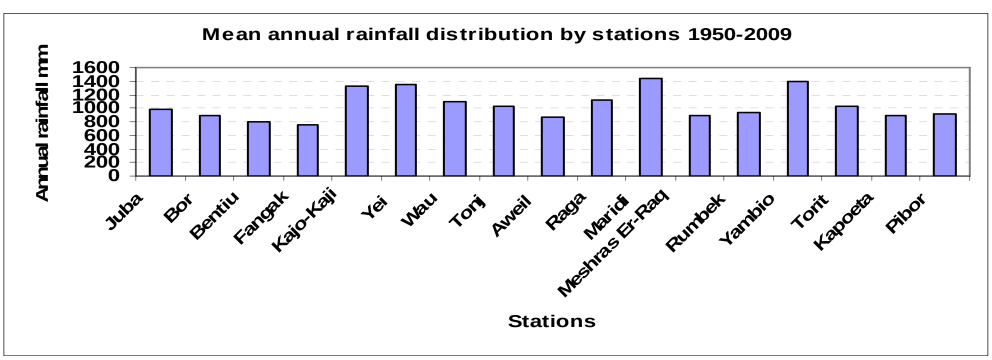

Figure5. 18: Annual Rainfall Distribution by stations name

5.2.1 Analysis of Point Precipitation Data

All hydrological observations, including precipitation measurements, sometimes are subjected to different errors and uncertainties. The error in precipitation observations may be affected by the size and type of the gauge , the wind speed , whether the precipitation is constituted by rain , snow , the size and distance of shielding buildings and trees , reading mistakes etc. the sum of all these errors may in turn carry over to a corresponding error in the water balance calculations.

In general, observational errors can be divided into random and systematic errors. Random errors may be less important and also more difficult to quantify. Systematic errors resulting from an unrecorded change in gauge location or shielding effect from trees or buildings from a certain date can be revealed with the help of a double mass curve. Before using the rainfall records of a station, it is necessary to first check the data for continuity and consistency. The continuity of a record may be broken with missing data due to many reasons such as damage or fault in a rain gauge during a period.

5.2.1.1 Identification of Homogeneous Rainfall Stations Based on Monthly Rainfall

The objective of this treatment is to preliminary classify the basin in to sub-basin which helps various studies such as filling missing values, rainfall elevation and runoff correlation, as well as categorizing streams in to this regions. The dimensionless computations of all stations where carried out for all 19 stations used in analyses and the profile plotted.

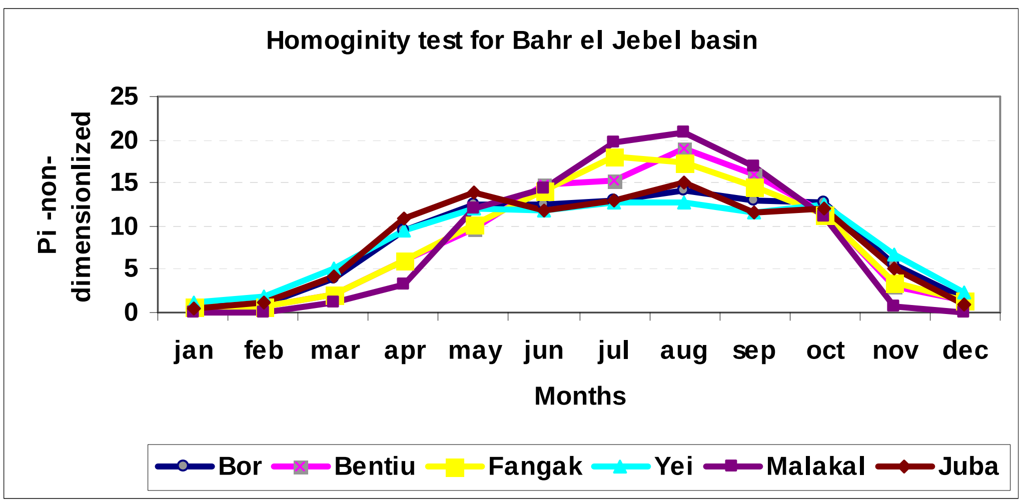

Figure5. 19: Bahr el Jebel Basin Homogeneity rainfall stations

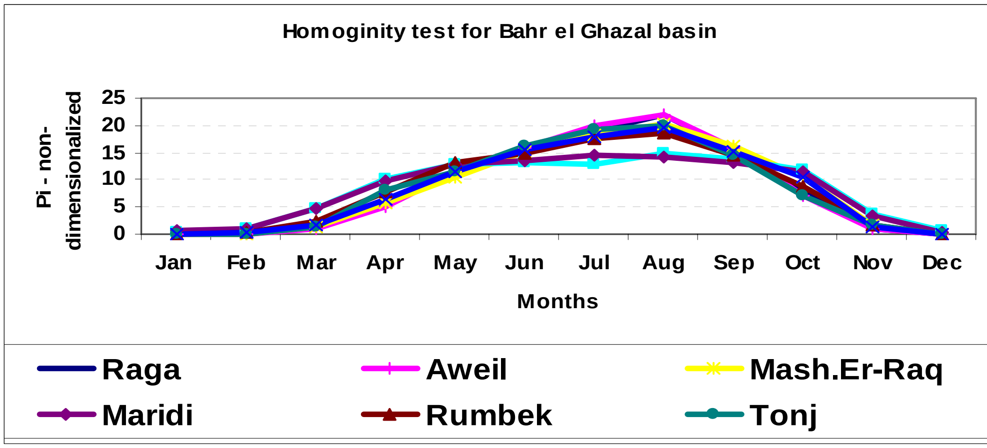

Figure5. 20: Bahr el Ghazal Basin Homogeneity rainfall stations

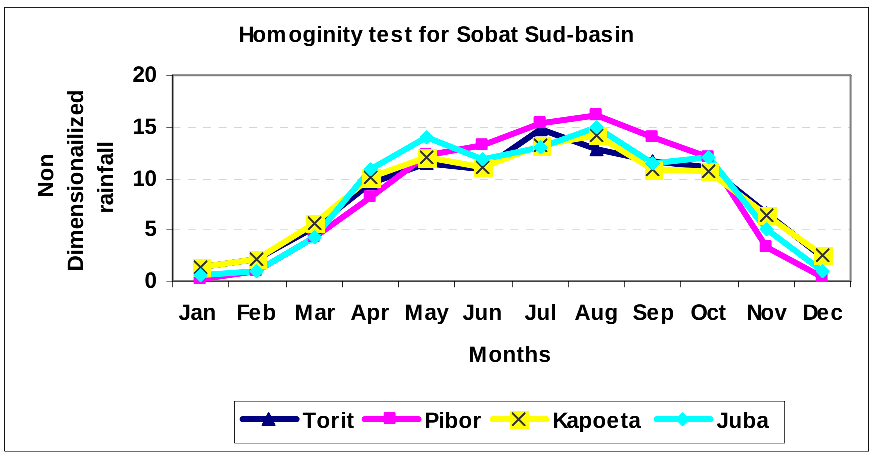

Figure5. 21: Sobat basin Homogeneity rainfall stations

As it is seen in the above figures (5.19, 5.20 and 5.21) all sub-basins showed similar climate and similar rainfall pattern. All stations in Sudd are mano-model in nature with the wet season located between June and August.

5.2.1.2 Rainfall data filling and extension

The short and missing of the data is always dominated all records both hydrology and metrology data, at study area , also most of the stations are not working properly, full of missing and stopped functioning .The data of each station has been checked, and missing data have been filled using simple interpolation techniques. The simple linear regression has been employed to extend the short term record of each station using the long-term records of nearby station , the criteria of doing this is that the climate features at the study area is look similar and there not much different in stations elevations . The same stops that use to extend the hydrological data have also been use here for rainfall data.

Table5. 4: Rainfall data extension models (Y and X are rainfall in mm)

No.	Station	Equation	(r)	(R^2)	Nearby station used
1	Bor	$Y = 0.6781X+20.213$	0.668	0.4468	Juba
2	Yei	$Y = -0.0054X^2+1.9261X+17.261$	0.76	0.5784	Juba
3	Bentiu	$Y = 0.6918X+10.716$	0.581	0.338	Juba
4	Fangak	$Y = 0.6749X+9.7945$	0.56	0.3122	Juba
5	Tonj	$Y = 0.7666X+15.389$	0.787	0.6188	Wau
6	Yambio	$Y = -0.0037X^2+1.5901X+34.077$	0.8	0.6397	Wau
7	Aweil	$Y = 0.7128X+6.0168$	0.75	0.5635	Wau
8	Meshras-Ra	$Y = 0.783X+3.0099$	0.81	0.6536	Wau
9	Raga	$Y = 0.847X+15.599$	0.76	0.578	Wau
10	Maridi	$Y = -0.0029X^2+1.4328X+36.659$	0.753	0.5682	Wau
11	Rumbek	$Y = 0.637X+19.288$	0.73	0.5343	Wau
12	Pibor	$Y = -0.0033X^2+1.4885X+57.169$	0.695	0.4827	Malakal
13	Kapoeta	$Y = -0.0021X^2+0.8877X+16.205$	0.573	0.3288	Juba
14	Torit	$Y = -0.0029X^2+1.2366X+19.034$	0.705	0.4967	Juba

r is correlation coefficient

R^2 is coefficient of determination

X is monthly rainfall in mm for nearby station. The test of hypothesis for a = 0 and b = 0 was done for all stations, and it find that a = 0 is not rejected for dry seasons (November to February) and is rejected for all remained period, while the b = 0 is rejected for all period.

5.2.1.3 Checking Consistency of Data by Double Mass Analysis

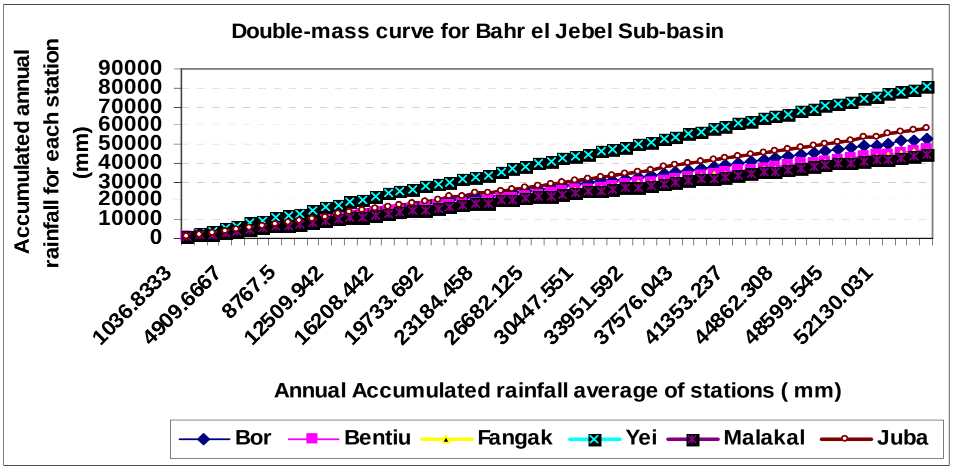

Figure5. 22: Bahr el Jebel rainfall double mass curve

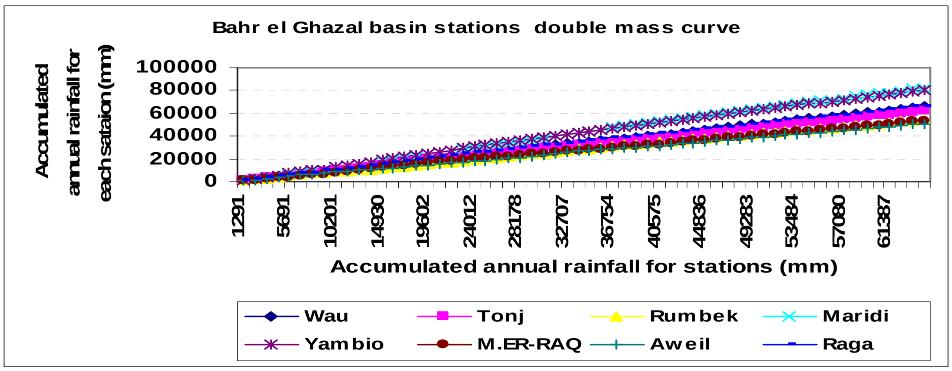

Figure5. 23: Bahr el Ghazal rainfall double mass curve

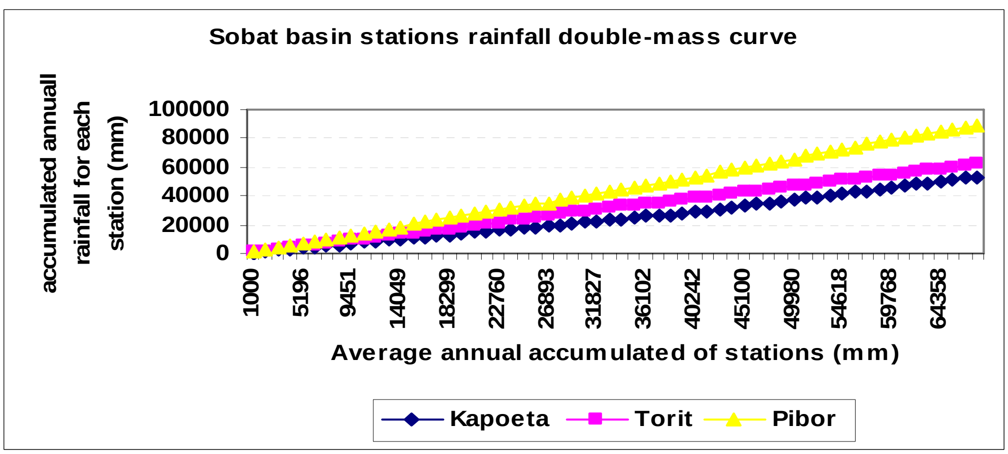

Figure5. 24: Sobat basin rainfall double mass curve

The curves show that all stations for the three sub-basins are consistent according to the criteria set for the double mass curve, if the data are consistent, the plot will be a straight line.

5.2.2 Sudd aerial rainfall distribution

Monthly rainfall records at six stations were used to derive a swamp rainfall series for the period 1950-2009 using Thiessen Polygon method. Long-term variations showed that the high flows around 1917 coincided with a period of high local rainfall but the period of high flows since 1961 was not reflected in Sudd rainfall. In other words, the high flows after 1961 were based on high rainfall in the lake region alone. This is important when comparing the changes in permanent and seasonal flooding. The using stations are: Bor, Fangak and Bentiu inside the swamp area while the Malakal, Juba and Yei from outside the swamp area.

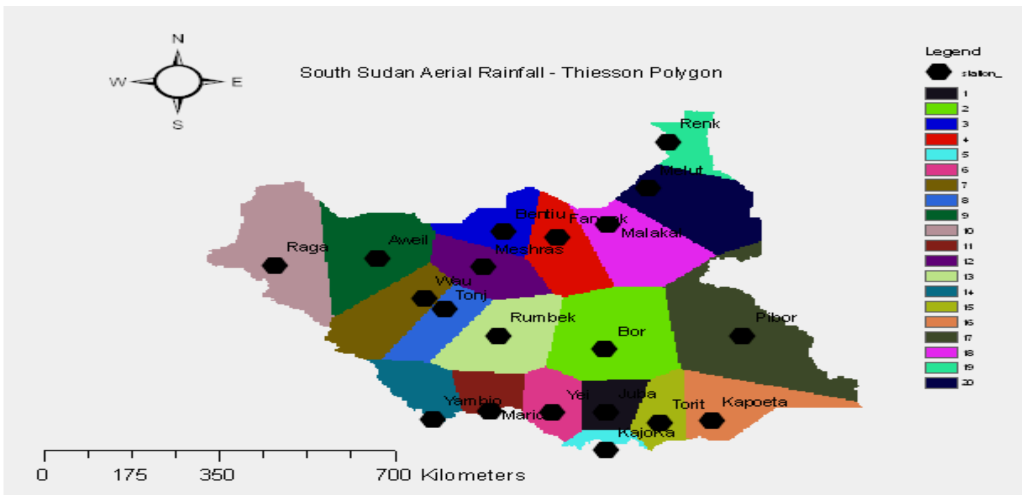

Figure5. 25: Thiessen polygon map of South Sudan

Table5. 5: Mean monthly rainfall over Sudd swamp 1950-2009

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean mm	5.2	7.9	27.2	67.1	105.6	115.6	134.1	140.7	122.6	105.7	38.3	11.9	882.0

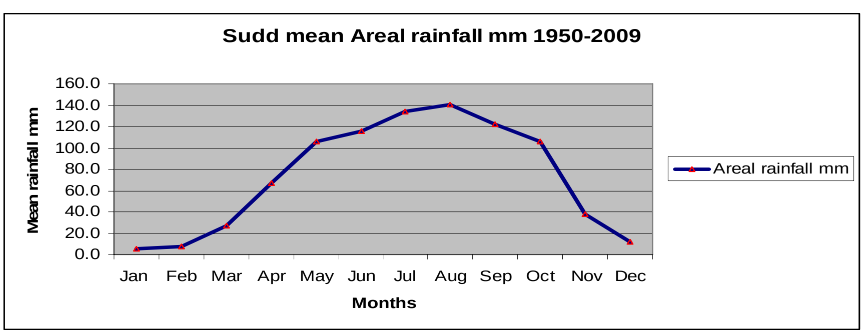

Figure5. 26: Mean monthly rainfall over swamp area

The wet period in a year lies between June and October and the dry period between November and April.

5.2.3 Temperature

Although solar radiation is the basic factor, there seems to be a closer parallelism between air temperature and transpiration. The temperature of the transpiring part is most closely related to the rate of evaporation.

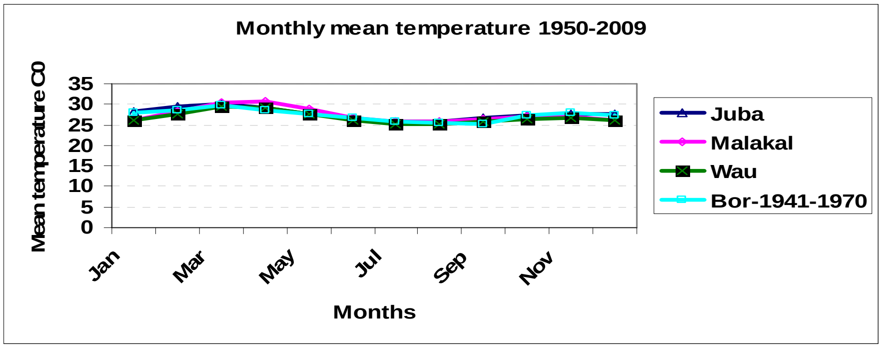

Figure5. 27: Mean monthly Temperature

Accordingly, for the three stations the hottest month is March and April with mean daily temperature 29 ^{0}C and the coldest month is January with temperature of 26 ^{0}C

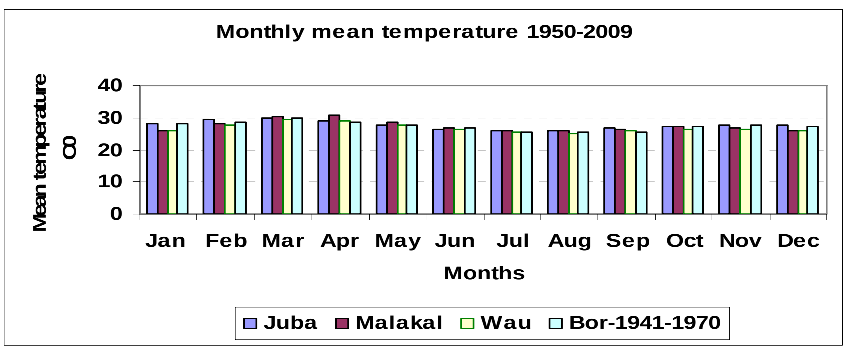

Figure5. 28: Mean monthly Temperature

It is clear in figure 5.28 that the temperature inside Sudd swamp area and outside look similar.

5.2.4 Evaporation

Realistic modeling of the swamps depends on a reasonable estimate of this factor; early experiments were carried out to measure evaporation from papyrus grown in tanks, but it was difficult to maintain vigorous growth. Penman (1963), discussing experiments by Migahid (1952) using tanks filled with papyrus and with open water, notes that the evaporation rates are about the same, and suggests that with the increased daytime wind speed observed, transpiration from the papyrus and evaporation from the open lagoon will be nearly equal. Open water evaporation has been estimated by the Penman method for Bor as 2150 mm/ year and the monthly averages were used to estimate the evaporation from flooded areas.

Knowledge of evaporation is a major importance in water resources assessment among others to determine the amount of water lost through the process of evaporation in the water balance computations of land, rivers, lakes, wetland and reservoirs. There are many ways of measurements and estimation of evaporation from large water bodies. Water balance approach, Mass transfer approach, Energy balance approach, pan evaporation approach, pitche and lysimeter measurements are some to mention. In order to compute potential evaporation or reference evapo-transpiration, a number of methodologies are available which include Penman and its modification based type equations like Penman-Monteith, Temperature type equations like; Blanely-Criddle method , Hamon and Thornthwaite method. (Mazengia2008).

In this study the temperature type equation was being adopted to estimate the evaporation over Sudd swamp area, that due to lack of the weather data. Here, in this research the method of Thornthwaite, penman moneith (Cropwat 8.0) and Hamon are applied for estimation of the potential evaporation over study area, using available records data from 2000 to 2009, the comparison was made between them in order to select the best method, but due to lack of the data, we select the method that has available data.

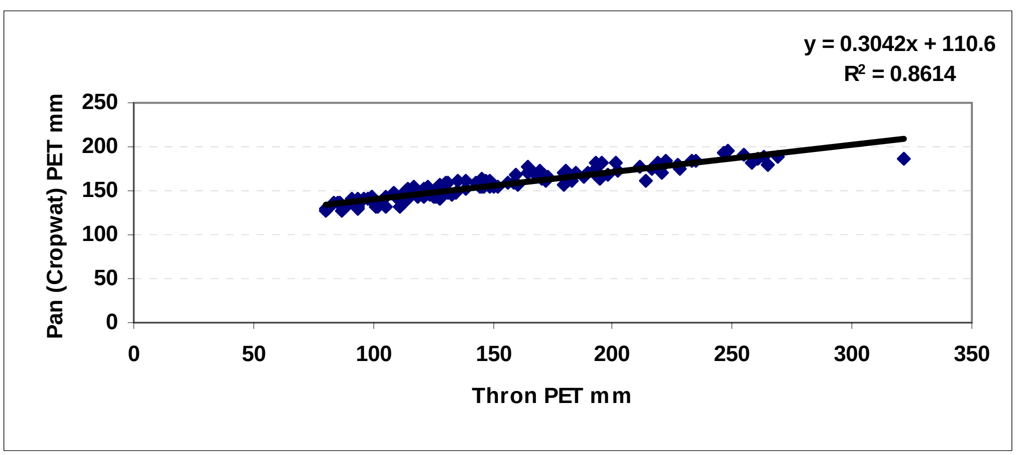

Figure5. 29: Comparison of pan ET with estimated ET for Thornthwaite method;

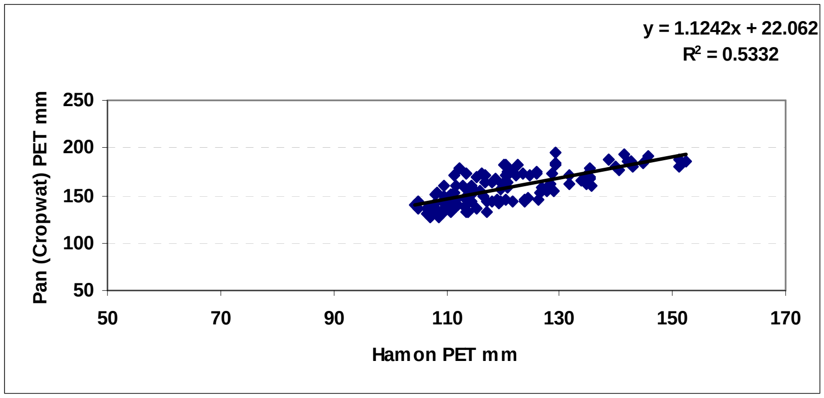

Figure5. 30: Comparison of pan ET with estimated ET for Hamon method;

As far as the R^2 values are concerned, both PET estimates methods correlated well with Panmenn FAO-Cropwat, with R^2 values of 0.86 for the thronthwaite method and 0.53 for the Hamon method. The Thronthwaite method has the highest R^2 value for Juba station, while the Hamon method result the low value, this because of the improvement made in the Thronthwaite method in the C constant was being change from C = 1.6 in the original equation to C = 2.

From the above obtained results the Thronthwaite method has be adapted in this research.

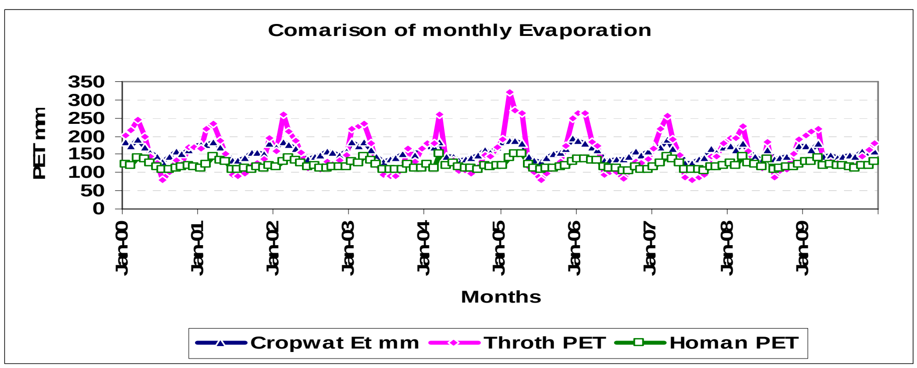

Figure5. 31: Comparison of monthly evaporation over study area

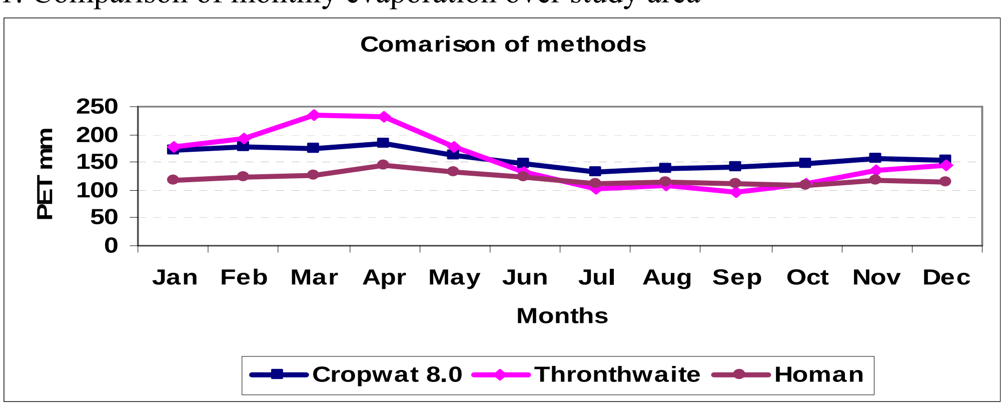

Figure5. 32: Comparison of average monthly PET 2000-2009

The comparison of the evaporation estimated from the three methods as in the fig 5.31 and fig 5.32 shows the highest values and lowest values are obtained from the Thronthwaite method; also the FAO recommended method of Panmenn shows high values than Hamon. Also the three methods show the similar trend shapes.

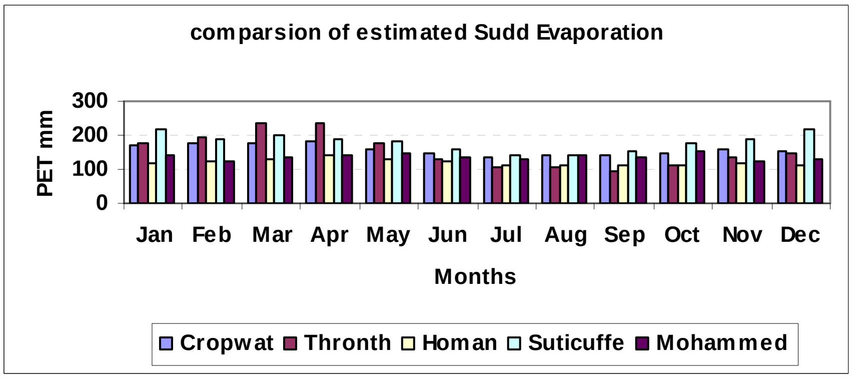

Figure5. 33: Comparison of the mean results

But it under estimates the values of ET as compared to penman moneith with two methods is some how different .An adjustment is made in parameter C of the Thornthwaite method by trial and error. Form the three methods, Thronthwaite and Hamon are adopted for the reason of availability of the data, with much consideration on the Thronthwaite method.

Table5. 6: Average potential evaporation estimated by Thronthwaite and Hamon

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
PET mm (Thro)	189	204	207	158	121	96	90	89	109	130	140	168	1706
PET mm (Hamon)	121	119	136	126	119	108	106	106	106	114	112	116	1395

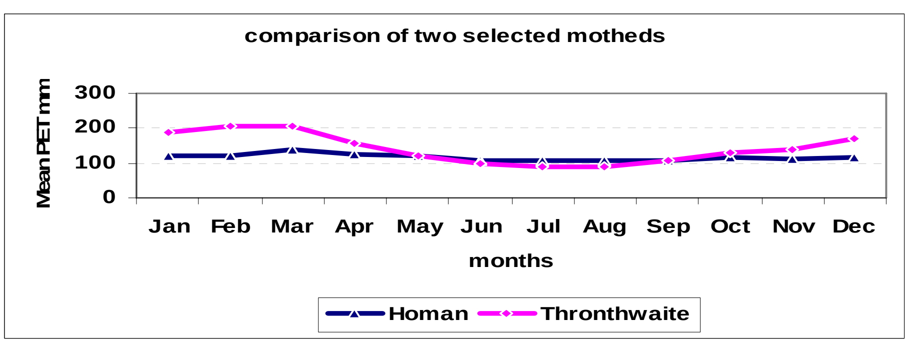

Figure5. 34: Comparison of Thronthwaite and Hamon methods

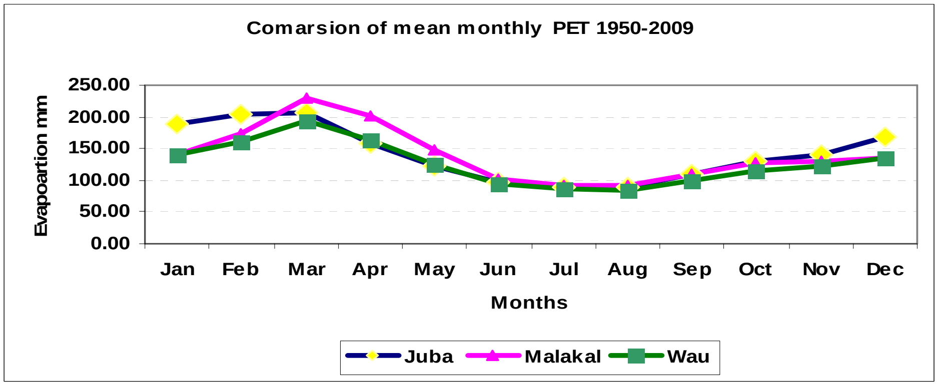

Figure5. 35: Estimated evaporation and comparison for three stations

For the comparison of the evaporation for the three stations Juba, Wau and Malakal , all stations show the highest evaporation is during dry seasons on the March and the lowest is during wet seasons on the July. Juba station shows highest values after Malakal station ,while Wau station show lowest one .

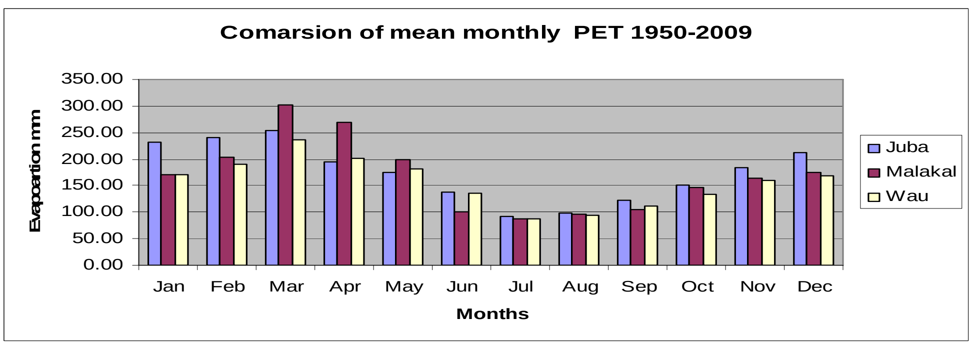

Figure5. 36: Estimated evaporation and comparison for three stations

Also the Thronthwaite estimated evaporation was compassion for three stations, Juba, Malakal and Wau. The Malakal station shows highest values and Wau station has lowest values. The maximum evaporation for the three stations occurs on the dry season in March while the low evaporation is in the wet season in July as the results of temperature variations.

CHAPTER SIX

6. RESULTS AND DISCUSSION

6.1 Hydrological data extension

For extension of the Mongalla station data records, the nonlinear regression technique is employed, with multiple linear relationships reached until lag of 10 months, Applying the method of nonlinear regression (equation 4.6) using records from Malakal station for period of 1912 to 1982, the following relationship has been established:

$Q_{Mon} = -711+0.9Q_{Mal(t)} -0.31Q_{Mal(t-1)} + 0.3Q_{Mal(t-2)} -0.004Q_{Mal(t-3)} +0.08Q_{Mal(t-4)} +0.25Q_{Mal(t-5)} + 0.66Q_{Mal(t-6)} - 0.005Q_{Mal(t-7)}+0.19Q_{Mal(t-8)}+0.24Q_{Mal(t-9)}+0.17Q_{Mal(t-10)}+error$

Where, Q_{Mon} = flow at Mongalla station m3/s

Q_{Mal} = flow at Malakal station m3/s , and t = time in moths

Table6. 1: The summary statistic of the regression is shown in the table below

Regression Statistics	
Multiple R	0.8
R Square	0.65
Adjusted R Square	0.64
Standard Error	266.45
Observations	842

6.2 Model out put results

Model outputs results involve five stages. These are the Sudd area, Sudd volume storage, Sudd outflow and soil water recharge stages. In this section the out put results are discussed in detail and comparison was done with the previous studies.

6.2.1 Model parameters estimated and water balance

Table 6.2 shows the out put of the model parameters estimated and water balance.

Table6. 2: Model parameters estimated

Parameters	Value	water balance components	Value(BCM)/mon
By-pass, x	1	Total Inflow	2746
inverse depth, k	0.85	(P-PET)*A	-1271
Recharge, r	0.35	Total Outflow	1312
outflow, smax	0.000214	Del V (Vi - Vi-1)	8
Initial V, Offext	13300	Recharge	155
Initial V, ontext	37000	Water balance	0
Runoff range div	1730		

Where By-bass x, is value of x in volume area linear releationship (A= kV^x)

K is depth inverse for flooding area

r is rate of soil water recharge

Outflow smax is value of c when the inflow is approached to outflow

Initial V off extend is minimum of flooding volume

Initial on extend is maximum of flooding volume

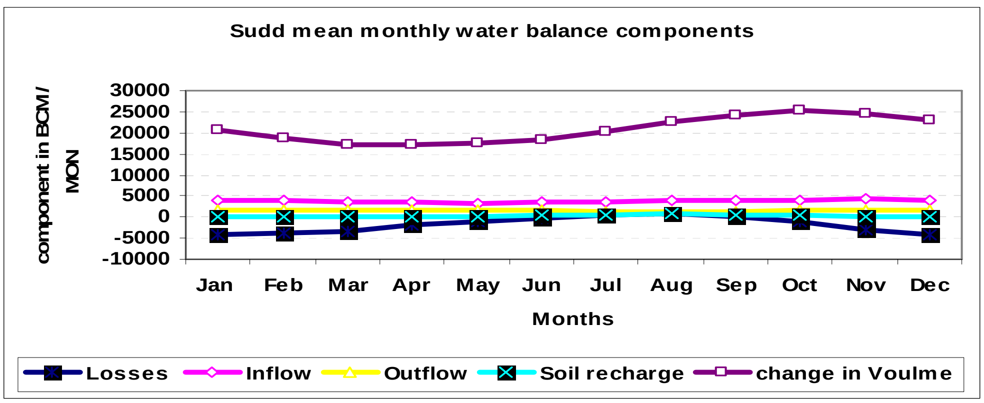

Figure6. 1: Sudd water balance components

in the above figure 6.1, the losses is amount of water evaporated over study area, as it clearly appeared that the evaporation and change in storage volumes are the dominated components of the Sudd water balance as they are fluctuate through out the seasons . The other components inflow, outflow and groundwater recharge are showing constant change through the seasons. Here also is showing clearly that the groundwater recharge is negligible compared with Sudd volume storage.

6.2.2 Analysis of the model parameters

The initial soil moisture recharge is estimated as 200 mm, but sensitivity analyses showed that the predictions of flooded area were little affected by varying this value; a 25% change gave only a 1% change in mean area. The form of the relationship, A = kV, was derived from survey data and the mean depth, 1/k, was estimated as 1.0 m; changing k by 25% also altered the mean area by 1%. This relationship was tested by substituting $A = kV^x$ while maintaining realistic values with x from 1.0 to 0.5 and varying k and x together to fit the mean values of A and V from the previous trial. The effect (Table 6.3) is to reduce the predicted mean area of seasonal swamp from 7400 to 4100 km, while the fit between observed and predicted areas of flooding deteriorates. Thus a value of x of 1.0 provides the best fit as well as corresponding to the available survey data.

Table6. 3: Effect of changing parameters on mean predicted areas.

X	1.0	0.9	0.8	0.7	0.6	0.5
K	1.0	2.59	6.71	17.4	45.1	116.8
Mean area (km2)	13640	13530	13430	13340	13260	13180
Mean minimum (km2)	10280	10450	10630	10820	11000	11150
Mean range (km2)	7440	6700	5980	5300	4650	4080

Thus although the model is shown to be sensitive to the form of the equation linking area and volume, which should be borne in mind as more data become available, the linear relationship derived from physical evidence gives a reasonable fit to measured areas of flooding. Thus one may deduce that the model gives an acceptable representation of the flooding regime within the limits of historical experience.

6.2.3 Estimate Sudd flooding area

The monthly series of flooded areas predicted by the model may be summarized in following figures. The number of years with maximum, minimum and range of flooded areas of different values is shown; these correspond to the total, permanent and seasonal swamps. The monthly series and the histograms demonstrate the fluctuations of the swamps and the dominant effect of the increased outflows from Lake Victoria after 1961-1964. This effect is most marked on the permanent swamps; the seasonal swamps, which depend on the torrents above Mongalla, have varied less than the permanent swamps.

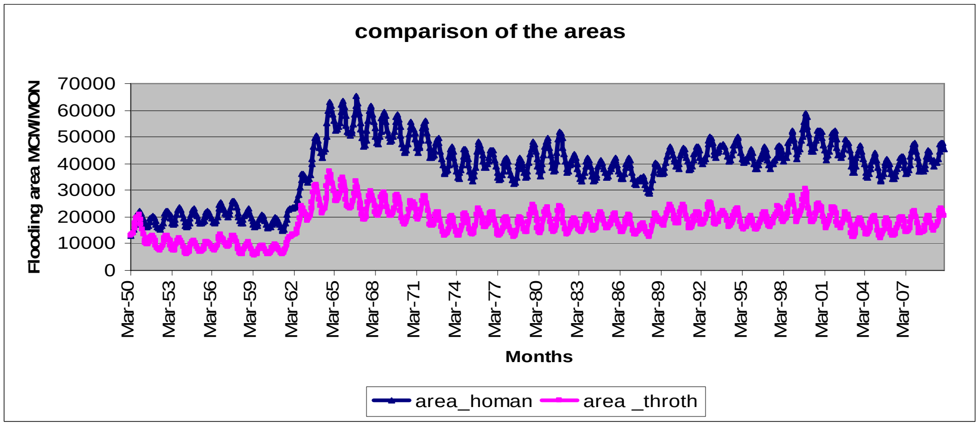

Figure6. 2: Comparison of the monthly flooding

In the figures, 6.2 the area estimated using thornthwiate evaporation is low than one of the Hamon method.

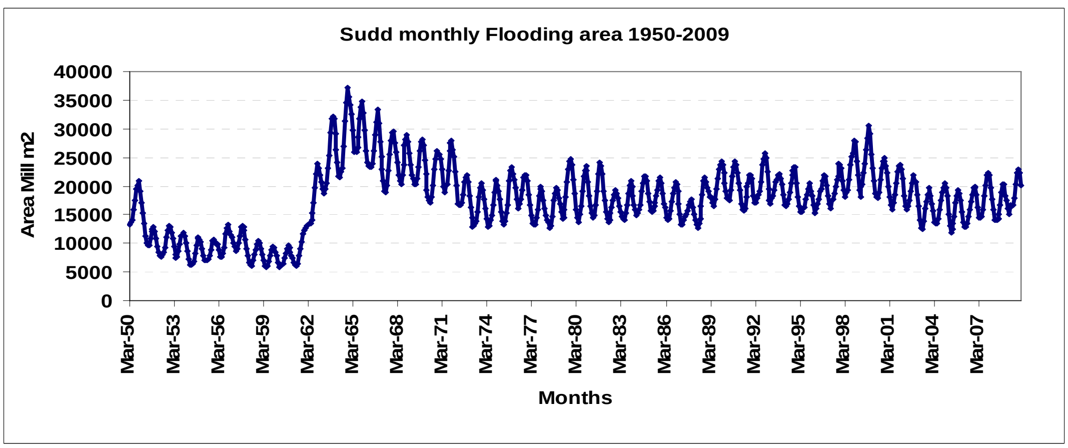

Figure6. 3: Sudd estimated flooding area

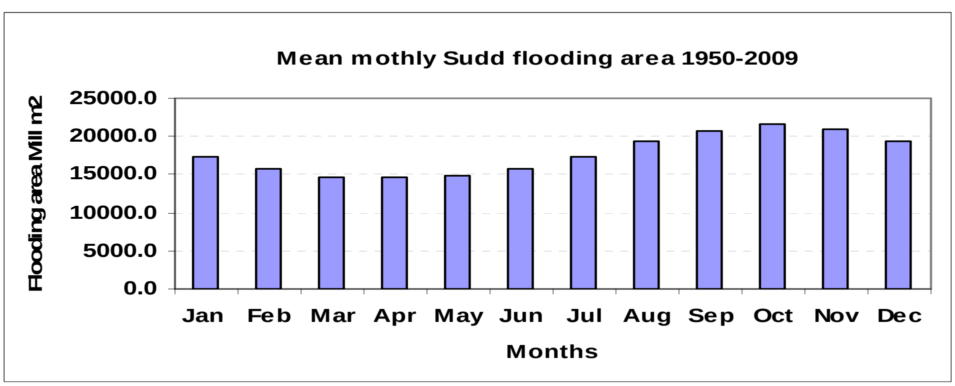

Figure6. 4: Average Sudd flooding area by Thronthwaite

The maximum Sudd flooding area is occurs on wet seasons in October, after three months lag of heavy rains at July, the minimum flooding area is on the dry seasons on April.

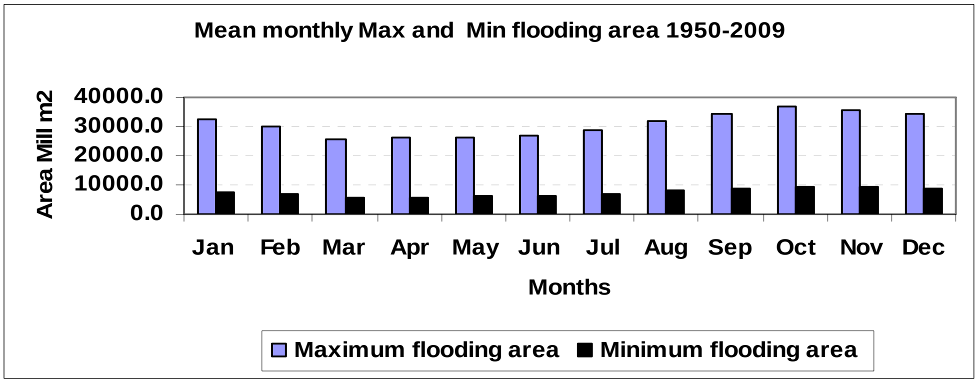

Figure6. 5: Average maximum and minimum Sudd flooding

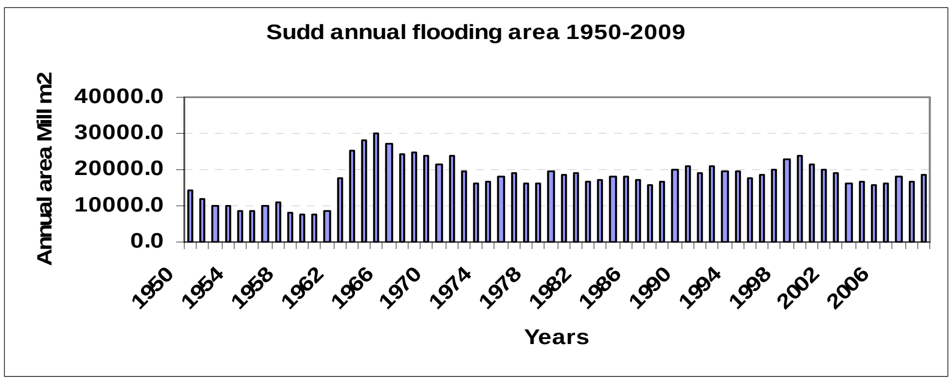

Figure6. 6: Annual flooding areas

6.2.4 Estimate Sudd swamp Volume

Volume of the sudd or the change in the Sudd volume was estimated from 1950 to 2009, as shown in the figures below it shows the shrinking and swelling of the sudd area.

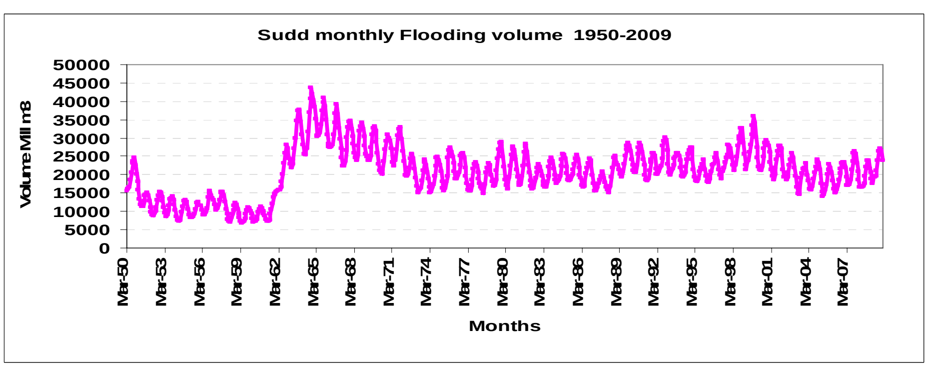

Figure6. 7: Sudd Monthly total volumes

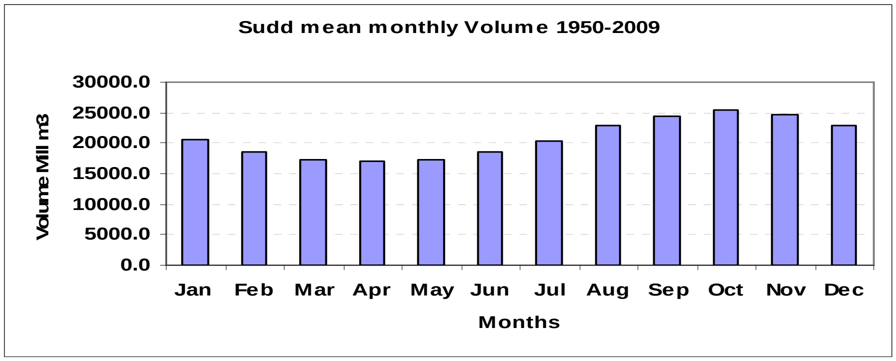

Figure6. 8: Sudd average monthly volumes

The maximum and minimum Sudd volumes are similarly occurring in same time with maximum and minimum flooding areas.

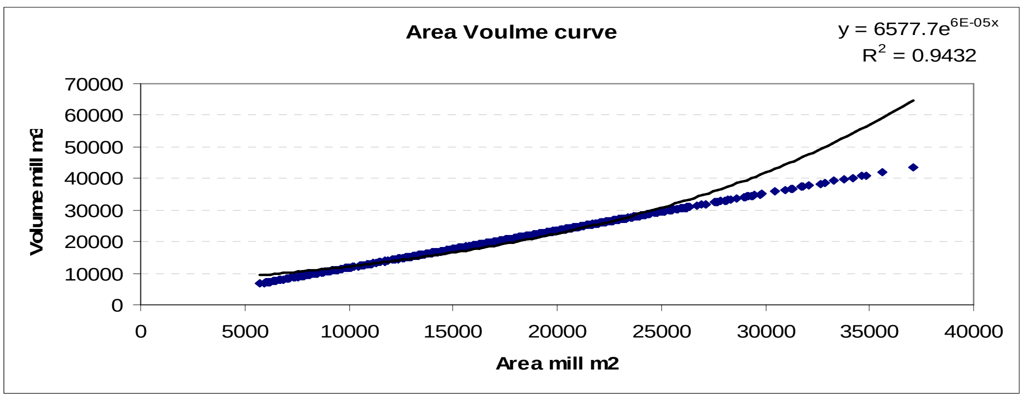

Figure6. 9: Sudd volume area curve relationship

The Sudd volume area relationship shows storage correlation of $R^2 = 0.94$, with form of $V = a\,e^{kh}$, here $kh = 6^{-5}X$ (where X is flooding area)

6.2.5 Sudd outflow

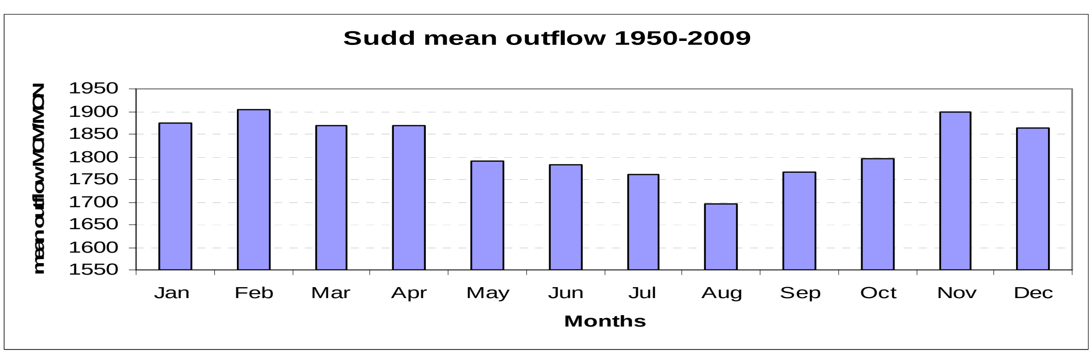

Figure6. 10: Sudd average outflows

The average monthly Sudd outflow from 1950 to 2009 is showing in the fig 6.10, the maximum out flow is found to occur at Novermber and February 1898.39 and 1903.91 MCM respectively and minimum outflow is 1696.79 MCM on August. The results of the outflow show the water losses due to evaporation, here as the flooding area of the Sudd is increase on August (See fig 6.4) lowest outflow is obtained, also as the Sudd inundation area is decrease during dry seasons from November to March, the high outflow is obtained. Here can be concluded that large flooding area high evaporation and low outflow, and small flooding area low evaporation and high outflow is obtained.

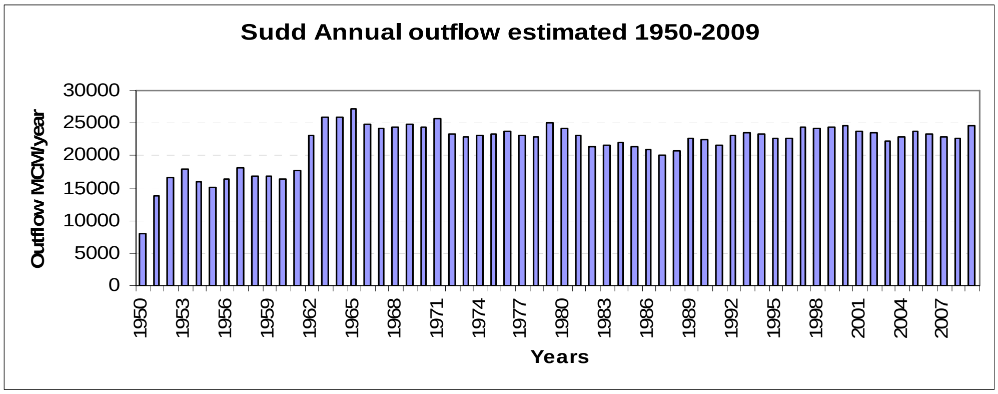

Figure6. 11: Sudd annual outflows

The average annual Sudd outflow is found as 21870.12 Mill m^2.

6.2.6 Groundwater recharge

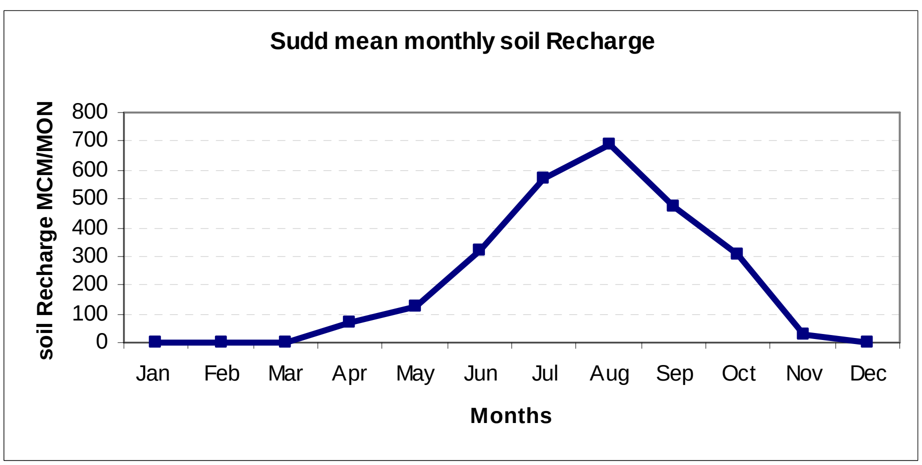

Figure6. 12: Average monthly soil recharge

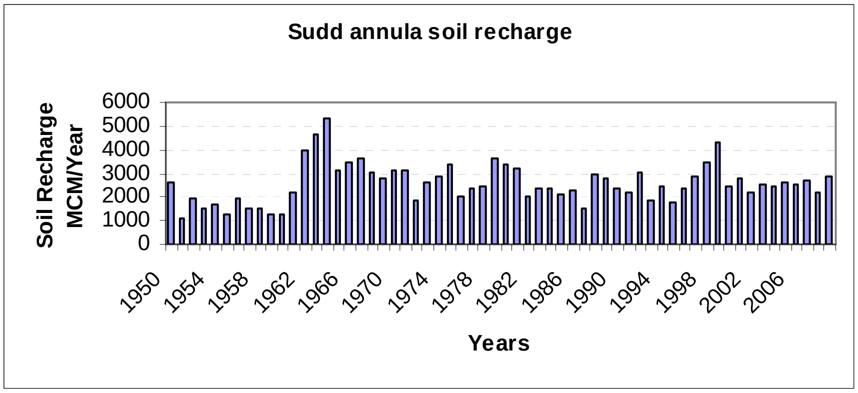

Figure6. 13: Annual Sudd soil recharge

The maximum groundwater recharge occurs on the August during the wet seasons and minimum is during dry seasons between November to March, and almost zero. This is as a result of water widely separation over large area during the seasons (swelling and shrinking of swamp area).

6.3 Model calibration and validation

The model evaluation involves two stages, which are known as calibration and verification stages. The calibration stage in which the model parameters are selected according to the set optimization criteria and the verification stage involve the extrapolation of the model parameters set in the calibration stage in to other set input data and evaluate the performance of the model (Awulachew 2001).

In this study the data quality are poor and study basin area is complex as mentioned previous , the area is received many ungauged streams , so is not inadequacy to use these data for model to be evaluated .

As the objective for using this model is to estimate the flooding area and volume of flood for the study area, as the field survey measurement of the area are not available for evaluated the output results of the model, which make our task more difficult for looking for other parameters for evaluation of the model. The only one available measured parameter is the Sudd outflow at Malakal, the model output parameters (k, r and change in volume) have used to estimate the outflow.

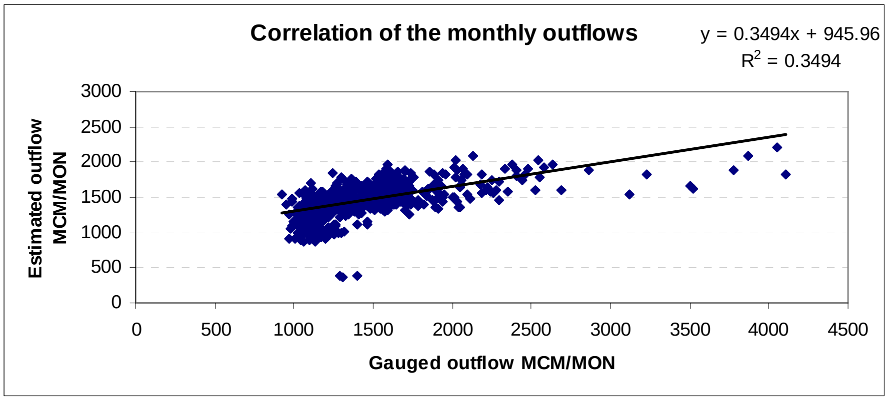

Figure6. 14: Correlation of the observed and estimated Sudd outflows.

As seen in the above fig the correlation coefficient is poor, which due to the inflow of ungauged torrents which flow into area at downstream of Mongalla.

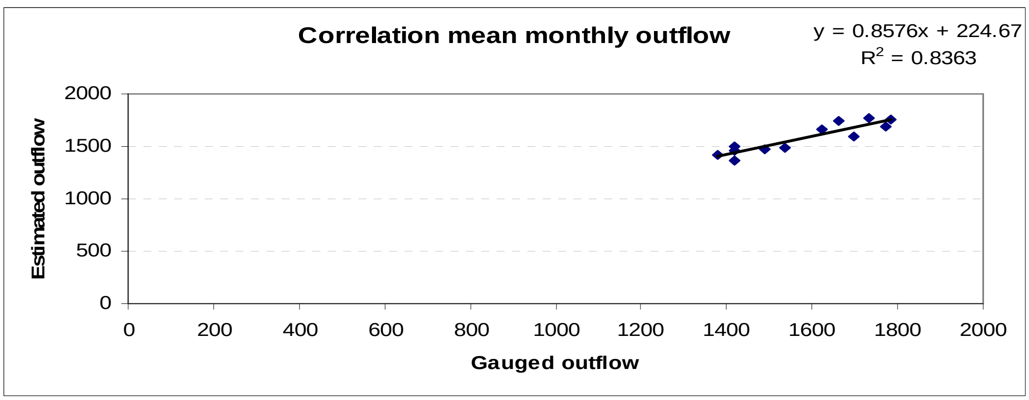

Figure6. 15: Correlation of average monthly sudd outflows

Here in the average monthly outflows the correlation coefficient is getting good comparison with monthly correlation, which indicted decrease in the measurement error.

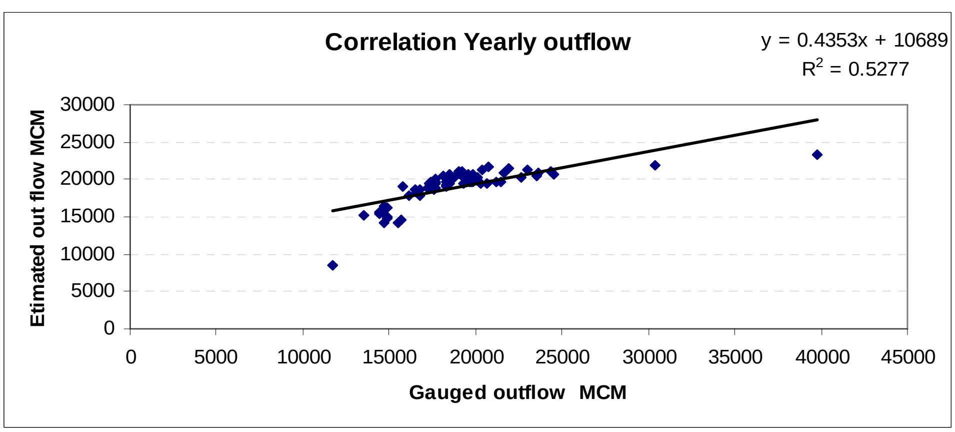

Figure6. 16 : Yearly sudd outflows correlation

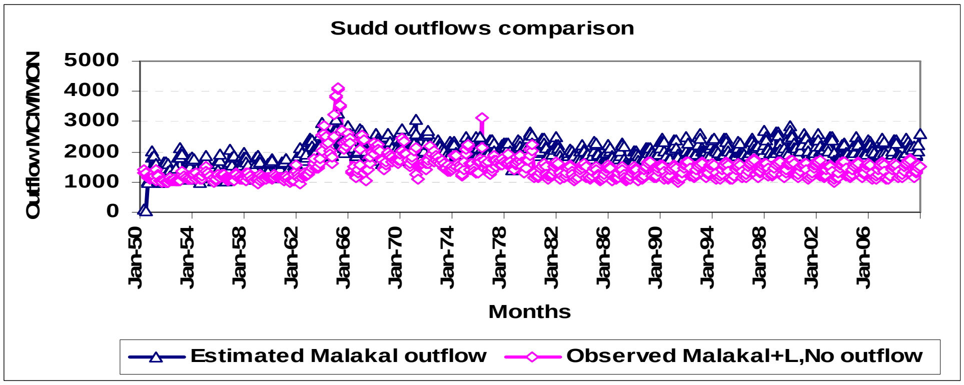

Figure6. 17 : Sudd outflows before correcting the error

The model estimated outflow is high than observed one, this difference can be explained as the ungauged inflow torrents downstream Mongalla .

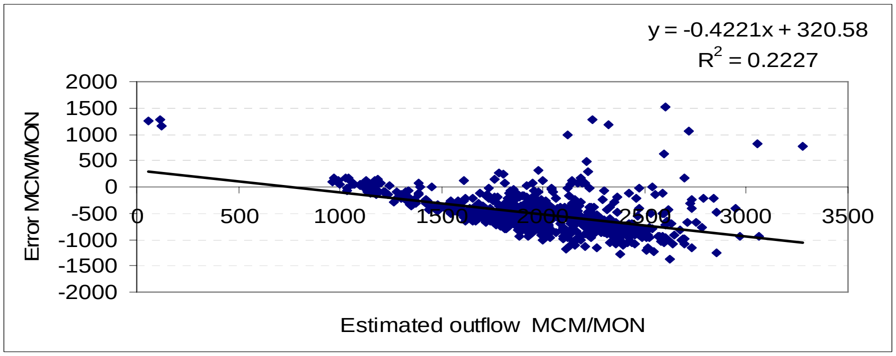

Figure6. 18: Error estimation

Here the error has been identified and estimated, and the all model estimated outflow are be corrected by adding the errors.

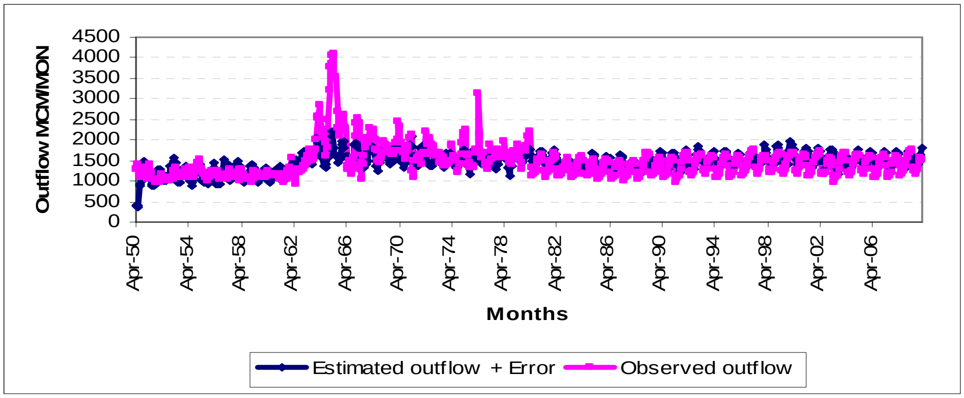

Figure6. 19: Sudd outflows after correction of the errors

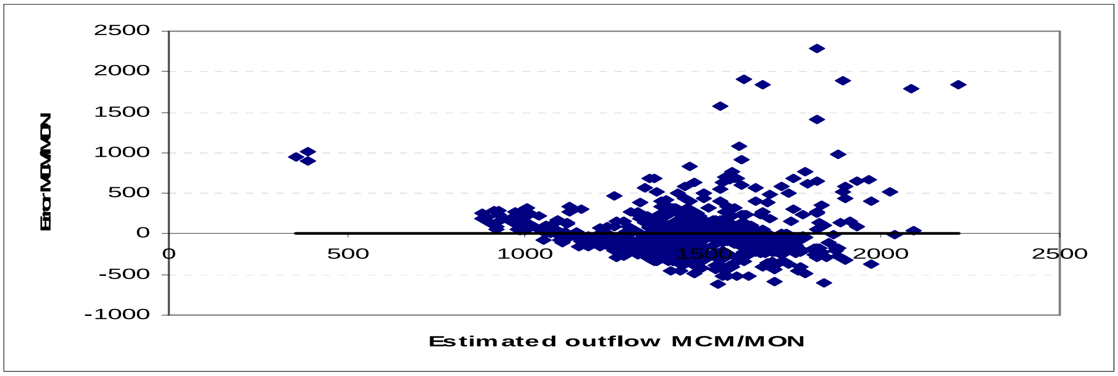

Figure6. 20: Estimated data error distribution

Here the fig 6.20 the errors are well distributing, after the corrected the error.

Table6. 4: Calibration results

Before correction				After correction			
Period	**N-S R2**	**RE**	**B**	**Period**	**N-S R2**	**RE**	**B**
1950-2009	-149.269	-34.887	-506.55	1950-2009	35	-0.0003	-0.004

6.4 Discussion of Results

6.4. 1 Sudd inundation area

In this study, it has been aimed to investigate the Sudd swamp area inundation throughout the seasons and years. The volume of the Sudd which is shrinking and swelling during the seasons and the inflow and outflow from the Sudd has also been investigated, on base of understanding the fluctuation of the hydrological factors in the area during different periods of times.

The Average annual inundation area from 1950 to 2009 of the Sudd area has been found as17684.27 Million m^2 with mean volume of 249660.2 Million m^3, this founding area is about 84 % of Mohammed 2004, 187 % of Sutcliffe 1905-1961, 80% of Sutcliffe 1961-1980 and 138 % of the Sutcliffe 1905-1980 . The difference between results can be explained as methodology employed for estimating the inputs as the evaporation, aerial rainfall and inflow torrents.

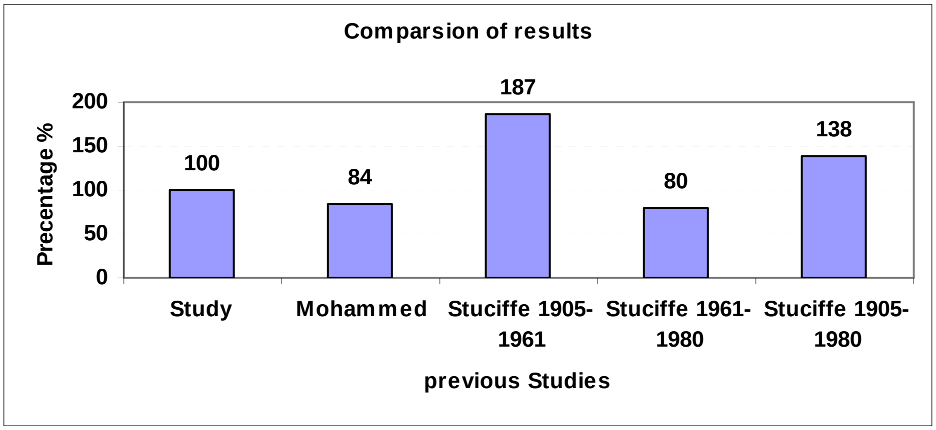

Figure6. 21: Results comparison

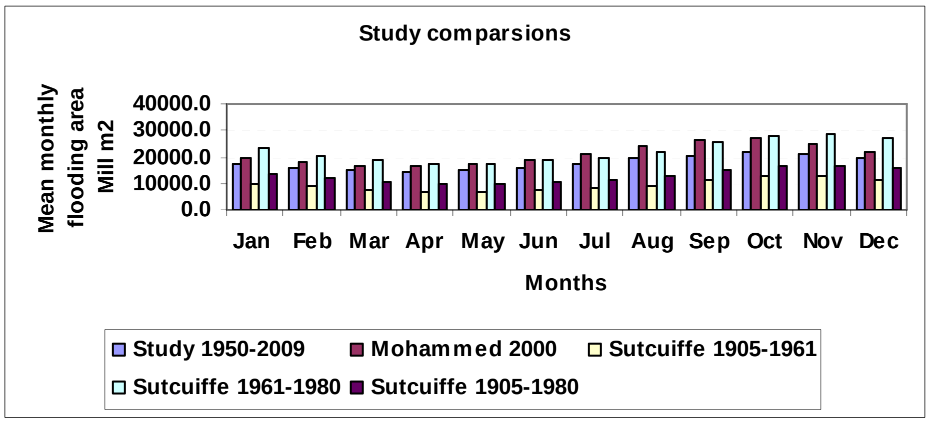

Figure6. 22: Sudd swamp inundation area comparisons

The estimated flooded area was compared with total area of the Bahr el Jebel basin which 38600 Mill m^2 according to estimation made by Mohammed 2004 which he used the evaporation map. The results of the comparison are presented in the figure below in the percentage.

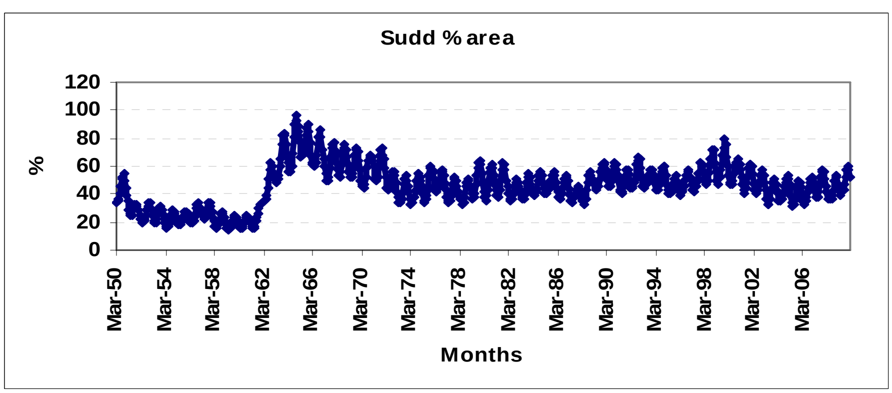

Figure6. 23: Percentage of Sudd flooding area from total basin area

From figure 6.23 , it clearly seen that on October 1964 the all area has inundated, 96.1% of the area under water also the maximum flooding area was occur on 1963 while the minimum flooding area is around 1958 to 1962.

6.4.2 Outflow forecasting

The inflow into Sudd Swamp area and model estimated outflow from Sudd Swamp area has been correlated on monthly time scale. In order to forecast the Sudd outflow from inflow at Mongalla gauge station, the predicted model shows the coefficient of determination of 0.773 which is quite good.

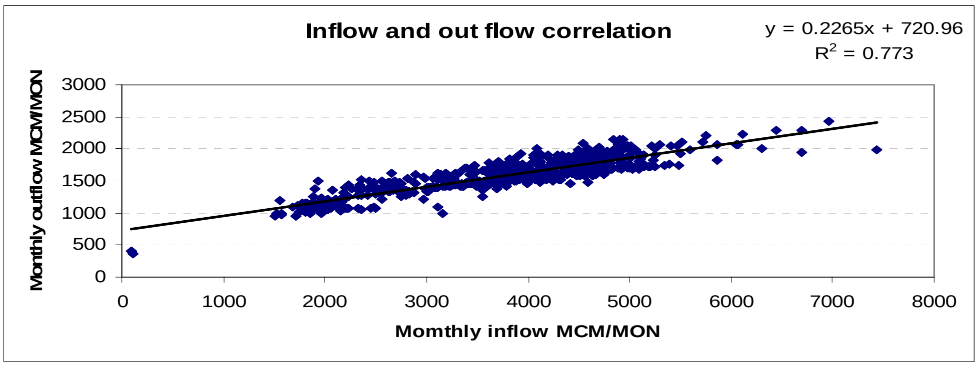

Figure6. 24: Sudd outflow forecasting

The Sudd inundation area can also be forecasting from the inflow at upstream at Mongalla station, this is not is always perfect, because the rainfall and other climate factors may be change over Sudd area. But here in the fig 6.25, the correction coefficient of 0.66 was obtained for correlation between the inflows to Sudd with inundation area.

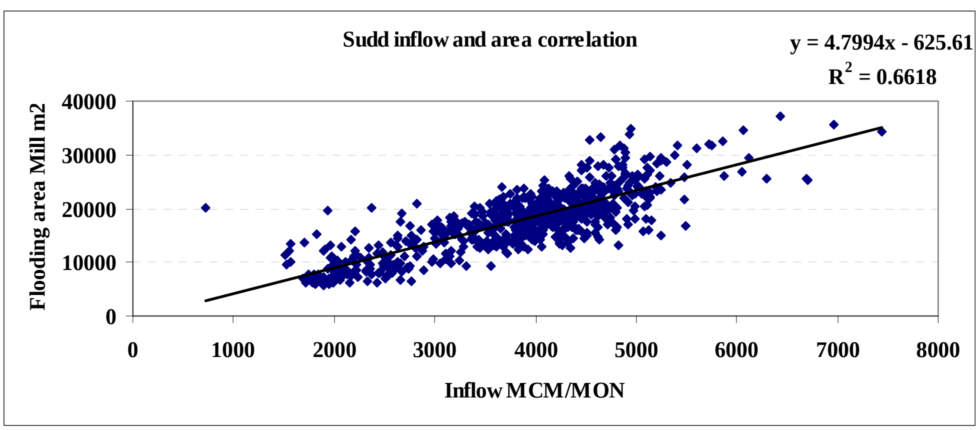

Figure6. 25: Sudd inflow and inundation area correlation

6.4.3 Dynamics of Sudd inundation area

The dynamic of the Sudd inundation area can be described based on the percentage of flooding area comparing with total area of the basin or South Sudan area, by doing this the flood frequency zone can be classify into three zone as in the table 6.5 below. The zones are permanent swamp, seasonal floodplains (regularly flooded and irregularly flooded), intermittently or occasionally flooded zone and dry lands. Such division reflects variation in hydro-ecological processes. The zones are composite ones: e.g. the intermittently flooded "zone" does not include only floodplains, but also islands within the belt where intermittent flooding occurs. The division into flood frequency zones captures differences in terms of hydrological processes (frequency and duration of inundation), and to a certain extent the differences in properties of the units. This is so because there is a feedback between geomorphology, vegetation and flood frequency. The link between flood frequency and geomorphology results from an inter-dependency between flood regime and the mechanisms of sediment deposition and the development of islands in the Sudd region.

Table6. 5: Sudd area % comparison and classification of flooding zone

Month	**Average flooding area Mill m2**	**% from the basin area 38600 Mill m2**	**% from area of South Sudan 6400000 Mill m2**	**% from basin delineated 200218 Mill m2**	**Remarks**
Jan	17446.21	45.19	0.27	8.71	Occassional swamp
Feb	15807.89	40.95	0.24	7.89	Occassional swamp
Mar	14731.5	38.16	0.23	7.35	Permanent swamp
Apr	14534.59	37.65	0.22	7.25	Permanent swamp
May	14782.08	38.29	0.23	7.38	Permanent swamp
Jun	15684.57	40.63	0.24	7.83	Occassional swamp
Jul	17342.54	44.92	0.27	8.66	Occassional swamp
Aug	19346.86	50.12	0.30	9.66	Seasonal swamp
Sep	20699.35	53.62	0.32	10.33	Seasonal swamp
Oct	21544.33	55.81	0.33	10.76	Seasonal swamp

Nov	20889.02	54.11	0.32	10.43	Seasonal swamp
Dec	19402.19	50.26	0.30	9.69	Seasonal swamp
Average	17684.26	45.81	3.31	8.83	

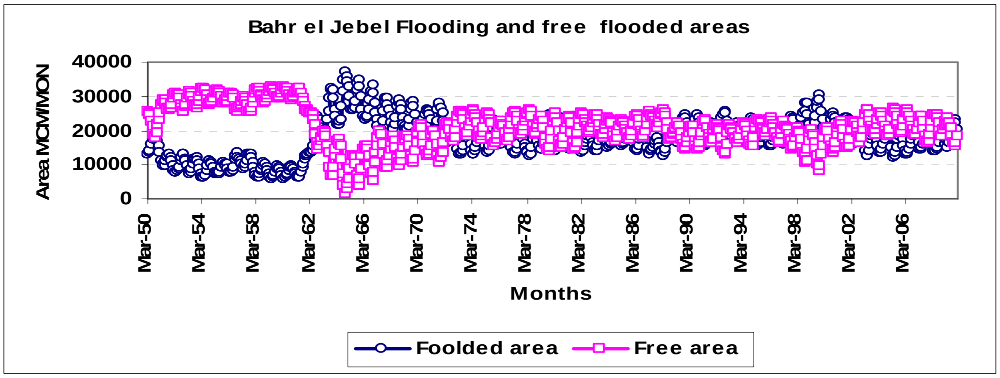

Figure6. 26: Sudd flooding and free areas usin area estimated by Mohammed

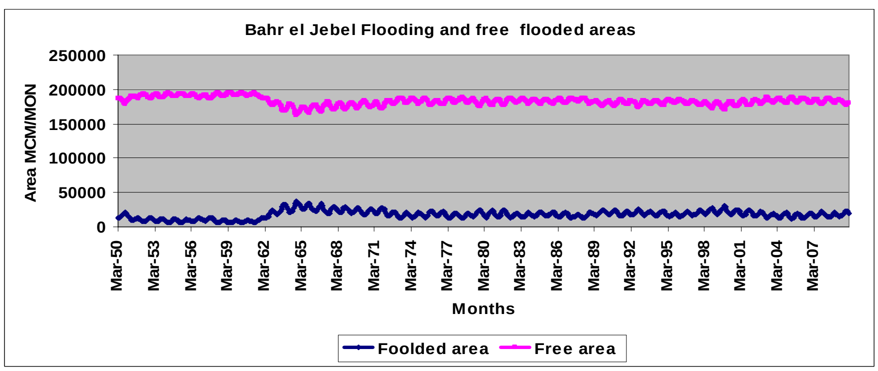

Figure6. 27: Flooding and free area result from area of watershed delineation

From fig 6.26 we can say that, reclaiming the free flooding land is required reduced flooding area, which can be done by drainage or diverging the Sudd water from downstream and upstream respectively. Also the comparison of the flooding and free areas using the calculated area resulting from the delineation watershed shows there large free flooding land in the basin fig 6.26

6.4.4 Estimation of the total yield flows of the three sub-basins

The catchments water balance will be adapted here , to estimated the total water yield flows of the three sub-basins of the Bahr el Jebel (Sudd basin) , Bahr el Ghazal and Sobat , so that the total outflow of the up White Nile can be identity at Malakal station . This has led to conformation of the estimation of the evaporation and aerial rainfall over three basins.

6.4.4.1 Bahr el Jebel water balance

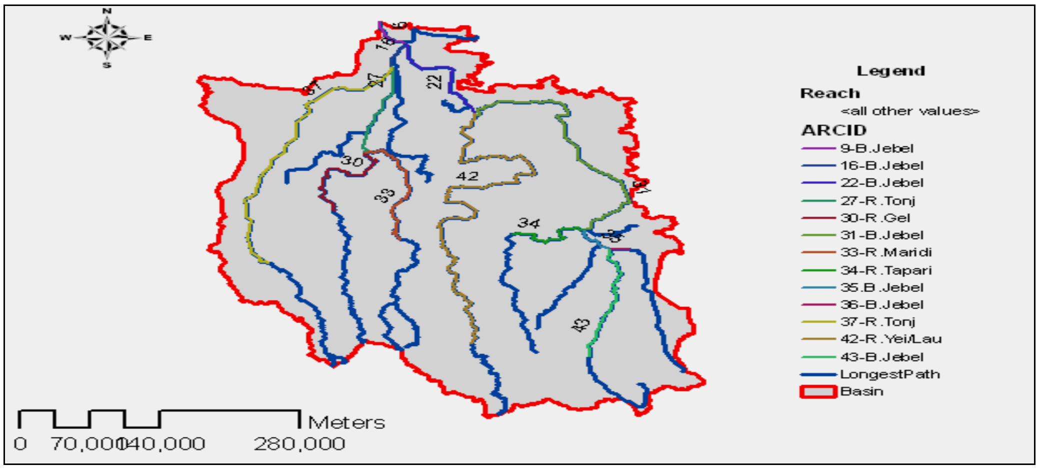

Figure6. 28: Bahr el Jebel watershed delineation using arcGIS-SWAT

The main problem of the calculation of the water balance of Bahr el Jebel watershed is the identification of the watershed boundary and estimation of total area of basin. Here the ARC/GIS-SWAT software was used to delineate the watershed, which resulted of the 200218 Mill m^2. This area has been used in the water balance equation; the inflow was be taken as the average monthly inflow at Mongalla station from 1950 to 2009 plus the torrent inflow of Tonj , Gel , Naam and Yei rivers and outflows are taken as model output average flows estimated at Malakal station minus Sobat at Hilleit Dollieb , also the average monthly rainfall and estimated PET from Thronthwiate method are used . The results of water balance calculation are in table 6.6:

Table6. 6: Bahr el Jebel water balance

Area = 200218 Mill m2						
Month	**Total Inflow MCM/MON**	**Malakal - H.Dolleib Outflow MCM/MON**	**Rainfall mm mm**	**PET mm mm**	**Soil Recharge MCM/MON**	**Change in storage dv/dt**
Jan	3342.15	1537.49	5.20	189.53	3.35	-35104.28
Feb	2863.52	1303.39	7.89	203.99	1.84	-37705.20
Mar	3097.28	1366.58	27.18	207.14	0.38	-34300.44
Apr	3126.29	1272.25	67.07	158.61	70.96	-16544.07

May	3614.34	1295.95	105.59	121.38	127.44	-969.38
Jun	3740.82	1303.80	115.63	96.49	316.64	5952.77
Jul	4158.29	1403.66	134.11	90.45	568.43	10927.94
Aug	4952.81	1482.74	140.74	89.92	685.87	12960.81
Sep	4964.63	1519.93	122.64	109.44	471.35	5616.83
Oct	4834.90	1648.11	105.71	129.82	303.47	-1944.12
Nov	4128.72	1608.18	38.29	140.97	24.75	-18064.38
Dec	3729.11	1640.04	11.90	168.39	1.45	-29244.54
Total	46552.87	17382.12	881.95	1706.12	2575.93	-138418.06

From table 6.6 the annual missing of the inflow was found as dv/dt = -138418.06 MCM/yr, this can be explined as missing from the inflow from ungauged streams. the unguaged streams are estimated by Sutcliffe and Parks 1999 for ,Tapari , and Gwir as ,440, and 120 MCM/yr respectively , which resulted the total of 560 MCM/yr .This estimated flows of ungauged streams should be added into water balance as inflows, there still missing of -137858.06 MCM/yr , which is very large compare with result of Mohammed 2004 was found -1150 MCM /yr; the different between two results can be explained as a result of included large basin area in this study and also the inflows torrents is all loss or are storaged as surface water some where within the watershed .

6.4.4.2 Bahr el Ghazal water balance

The result of the delineation of the Bahr el Ghazal watershed results the area of 154331 Mill m^2, this area was used to calculate the water balance of the catchment, as in the table 6.7:

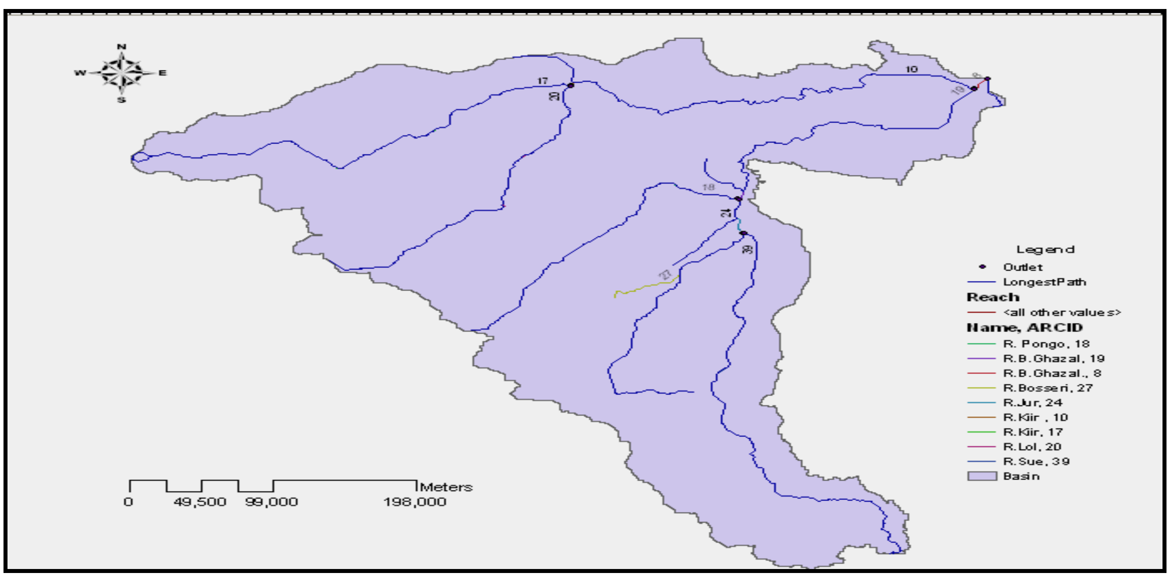

Figure6. 29: Bahr el Ghazal watershed delineation using arcGIS-SWAT

Table6. 7: Bahr el Ghazal water balance

Months	Inflow Jur flow MCM/MON	Inflow Lol flow MCM/MON	Outflow Khor Dolleib MCM/MON	Rainfall mm	PET Mm	Chang in storage dv/dt
Jan	44.30	10.20	22.60	3.16	140.21	-21119.47
Feb	11.00	2.00	31.50	5.63	160.79	-23964.31
Mar	0.00	0.60	41.70	29.33	192.72	-25256.15
Apr	30.30	1.60	29.40	80.49	163.82	-12856.89
May	130.00	14.60	22.60	127.92	125.22	538.43
Jun	248.00	106.00	24.60	159.43	95.34	10220.40
Jul	436.00	293.00	28.50	181.49	85.88	15455.93
Aug	803.00	652.00	28.50	197.56	84.32	18903.32
Sep	1310.00	995.00	17.90	157.86	98.78	11404.83
Oct	1380.00	851.00	18.20	104.48	115.48	514.97
Nov	646.00	268.00	13.70	23.30	123.50	-14563.51
Dec	180.00	49.10	12.50	2.74	134.17	-20066.68
Total	5218.60	3243.10	291.70	1073.39	1520.22	-60789.12

The missing inflows of dv/dt = -60789.12 MCM/yr is obtained , which is explained as a result of ungauged stream of Raaba el Zarqa (100 MCM/yr) , Kiir or Bahr el Arba (300 MCM/yr) and spilling from Bahr el Jebel (6000 MCM/ yr) , the total of ungauged streams is 6400 MCM/yr , adding this total is result of dv/dt = -54389.12 MCM/yr , this is still large comparing with Mohammed result of -24480 MCM/yr , the different also can be explained as including large area in this study and also neglecting of soil and groundwater recharge .

6.4.4.3 Sobat water balance

The area of Sobat River basin was found as 255901 Mill m^2 , but this area was not used in water balance calculation as some part from the Baro-Akobo basin in Ethiopia was involve in DEM map. Here the area of Sobat estimating by Mohammed was adapted.

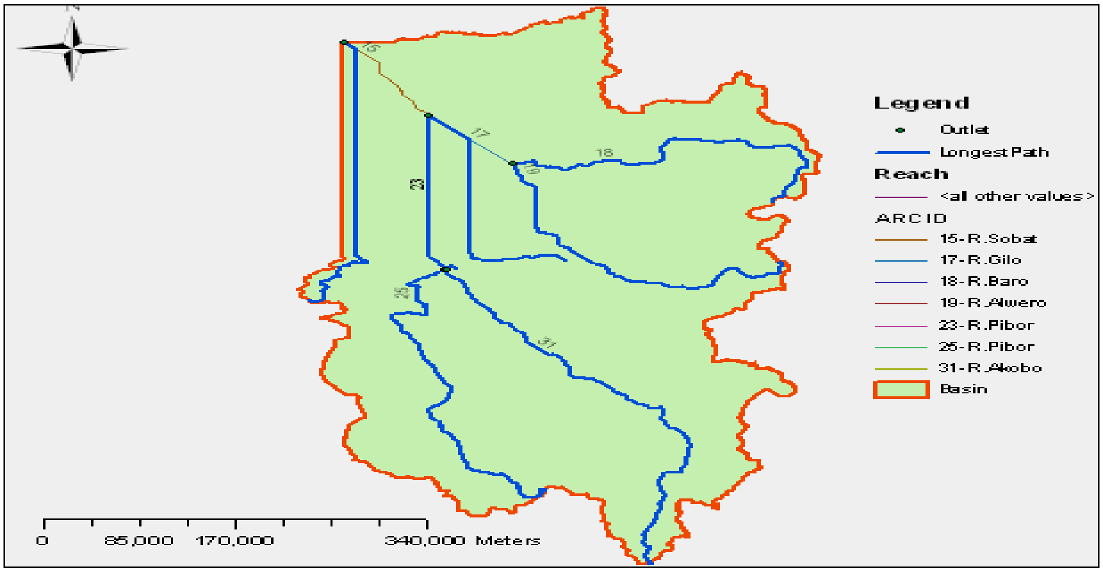

Figure6. 30: Sobat watershed delineation using arcGIS-SWAT

Table6. 8: Sobat water balance

Area = 42900000000						
Months	**Sobat Outflow at H Dolleib MCM/MO**	**Baro inflow at Gambela MCM/MON**	**Gila inflow at ungnido MCM/MON**	**Rainffal mm**	**PET mm**	**Change in storage dv/dt**
Jan	1195.08	223.84	2.92	14.99	140.18	-6338.92
Feb	660.51	127.72	1.37	27.15	172.71	-6776.03
Mar	479.21	124.09	2.82	84.14	229.76	-6599.06
Apr	429.19	131.59	2.54	153.79	200.81	-2312.22
May	546.96	386.70	6.06	202.48	147.21	2216.88
Jun	880.52	981.27	8.46	204.83	102.77	4487.44
Jul	1284.75	1925.47	9.70	248.59	92.45	7349.03
Aug	1569.61	2450.55	12.37	248.88	90.92	7669.50
Sep	1726.07	2717.91	11.24	212.04	109.01	5423.24
Oct	1910.77	1991.02	10.08	192.67	128.62	2838.08
Nov	1870.79	806.60	5.88	85.93	129.89	-2944.08
Dec	1731.26	387.10	4.12	26.94	135.13	-5981.03
total	14284.71	12253.87	77.57	1702.43	1679.45	-967.17

The missing of dv/dt = -967.17 was founded, and is also result of ungauged streams of Pibor (1040 MCM/yr) , Akobo (370 MCM/yr) and Mokwai (1300 MCM/yr) , the total of 2710 MCM/yr was estimated from ungauged streams (Sutcliffe and Parks 1999) . adding this total we have missing from outflows of dv/dt = 1742.83 MCM/yr , which is totally different compared with -3120

MCM/yr missing in inflows obtained by Mohammed , the different can be explained as soil and groundwater recharge and spills from streams into surrounding wetlands

6.4.4.4 Total out flow at Malakal

The total yield of the three Sub-basins can be explained as in the figure 6.30, the total flow gain at Malakal station is 31958.53 MCM/yr, this result is look small compare with previous studies, Mohammed 2005 found total gain at Malakal = 36 BMC/yr while Sutcliffe and Parks were found Amount of 21 BMC / year, the different is much big and can be explained as the different on the areas used for estimation of the water balance components, and Also as the study is not considering the soil water recharge or groundwater inflow and outflow for Bahr el Ghazal and Sobat basins .

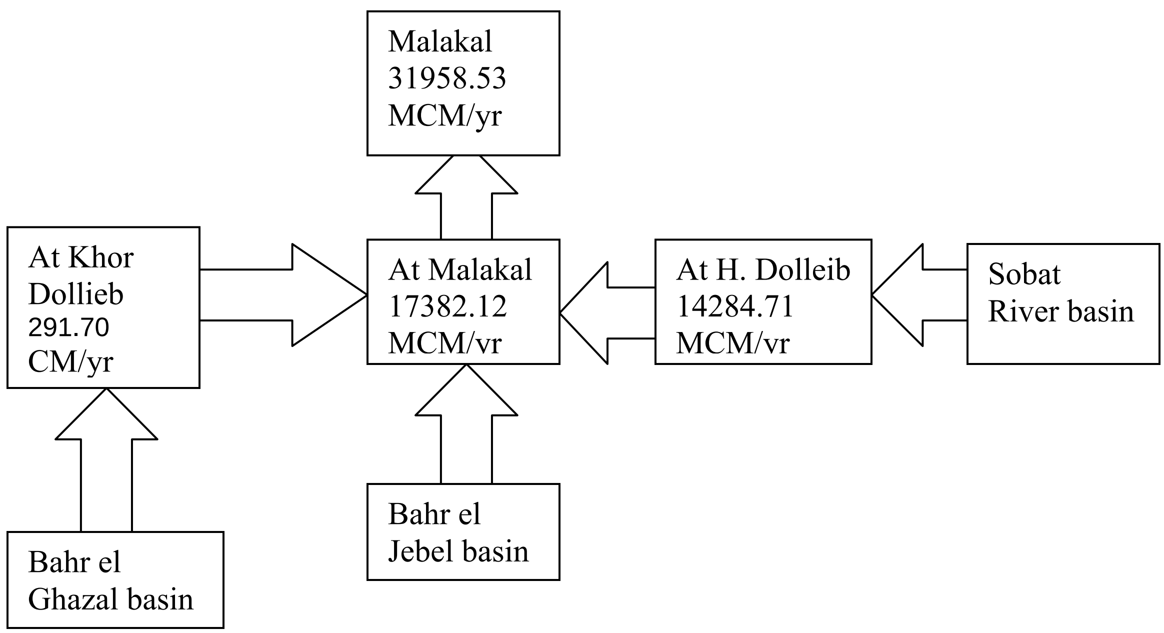

Figure6. 31: Outflow of the White Nile at Malakal

6.4.5 The Sudd area sensitivity to temperature and rainfall variations

One of our objectives is to determine the sensitivity of the Sudd area inundation to sustained changes in rainfall and temperature. This was done by using simple climate change approach, of increase or decrease both temperature and rainfall over the Sudd area. The temperature was being increase by 1, 2 and 3 ^{0}C , this base on the criteria of the increase in globe temperatures, and rainfall was being increase and decrease by 10%, 15% and 25%. By doing so the three scenarios was developed as following:

1- Scenario one

In this scenario the temperature was increase by 1 ^{0}C and rainfall was increased and decreased by 10%, 15% and 25%. This variation of the rainfall with constant temperature led to the follow results in the tables below; in this scenario the Sudd annual inundation area is decrease by 7.9% up to 28.42 %, here the impact of the temperature is high compare with impact of the rainfall which is less.

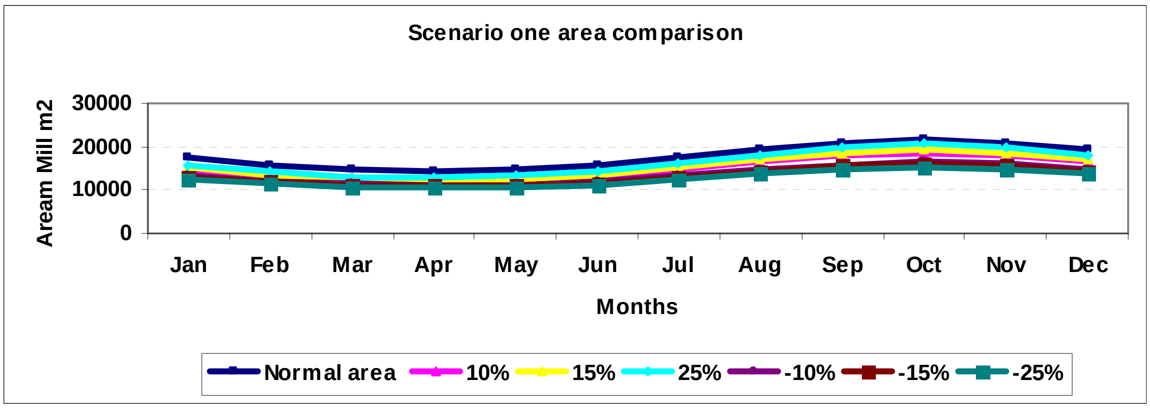

Figure6. 32: Scenario one average monthly area

The normal area is the area estimated by model which is the results from the study , as it clearly show in the fig 6.32 it is largest than the areas estimated after affects of the temperatures and rainfalls change , the fig also is shown the high reduction in area when the temperature is increase and rainfall is reduced .

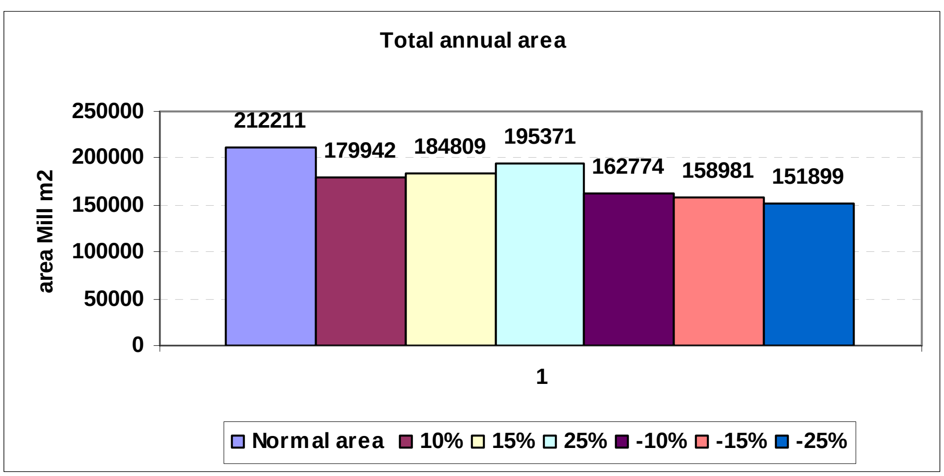

Figure6. 33: Annual total flooding areas

Here the total annual area is reduced from 212211.19 Mill m^2 to the only 151898.96 Mill m^2, the reduction in the area is around 28.42 % of normal area. This is got under worst conditions of increase on the temperature and reducing in rainfall.

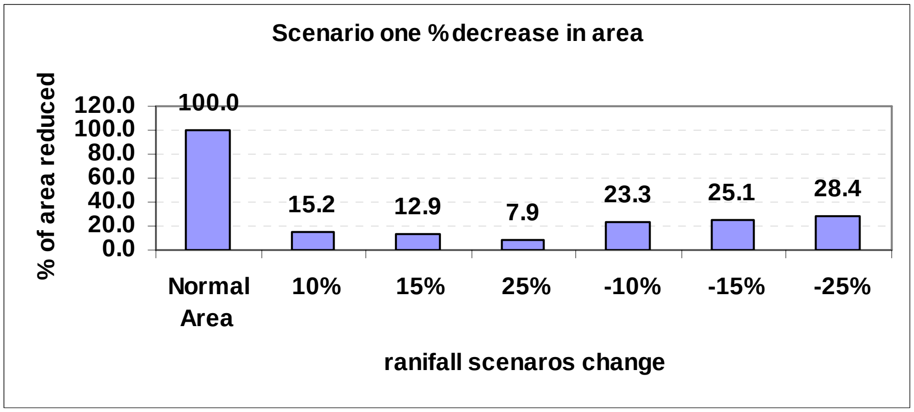

Figure6. 34: Percentage reduction of annual area result from scenario one

Table6. 9: Sudd average monthly percentage change from scenario one

1 degree increase in temperature													
		increase in rainfall						decrease in rainfall					
		10%		15%		25%		10%		15%		25%	
Months	Normal Area	Area (Mil m2)	% from normal area	Area (Mil m2)	% from normal area	Area (Mil m2)	% from normal area	Area (Mil m2)	% from normal area	Area (Mil m2)	% from normal area	Area (Mil m2)	% from normal area
Jan	17446.22	14668.5	84.0784	15037.49	86.19342	15839.93	90.7929	13371.36	76.64333	13085.94	75.00729	12554.19	71.95938
Feb	15807.89	13165.86	83.28661	13466.21	85.18661	14119.44	89.31894	12110.15	76.60825	11877.86	75.13879	11445.11	72.40122
Mar	14731.51	12225.82	82.99097	12482.31	84.73204	13039.71	88.51576	11323.14	76.86341	11124.29	75.51357	10753.55	72.99693
Apr	14534.6	12072.55	83.06079	12330.4	84.83487	12889.68	88.68276	11161.74	76.79427	10960.27	75.40817	10583.71	72.81735
May	14782.09	12298.94	83.20164	12586.19	85.14486	13207.8	89.35003	11280.83	76.31421	11054.66	74.78413	10630.97	71.91788
Jun	15684.58	13147.78	83.82615	13477.51	85.92841	14190.52	90.47433	11977.66	76.36587	11717.41	74.70654	11229.55	71.59615
Jul	17342.55	14716.73	84.85912	15119.31	87.18045	15990.12	92.20168	13289.19	76.62768	12971.94	74.79838	12377.66	71.37163
Aug	19346.86	16622.12	85.91637	17111.74	88.44712	18172.04	93.92761	14889.58	76.96122	14505.45	74.97572	13786.96	71.26203
Sep	20699.35	17886.32	86.41006	18445	89.10905	19656.84	94.96357	15915.06	76.88678	15479.33	74.78174	14665.87	70.85184
Oct	21544.33	18655.15	86.58959	19257.16	89.38389	20565.15	95.45501	16536.79	76.75701	16069.88	74.58981	15199.65	70.55057
Nov	20889.03	17970.07	86.02638	18521.23	88.66487	19719.32	94.40037	16032.87	76.7526	15606.39	74.71094	14811.6	70.90612
Dec	19402.2	16511.95	85.10353	16974.54	87.48772	17980.3	92.67147	14885.3	76.71966	14527.26	74.87433	13860.15	71.43597

Table6. 10: Sudd average monthly percentage change from scenario two

2 degree increase in temperature													
	Normal Area	increase in rainfall						decrease in rainfall					
Months		10%	% area	15	% area	25%	% area	10%	%area	15%	% area	25%	% area
Jan	17446.22	11812.61	67.70873	12049.81	69.06829	12557.91	71.98069	10961.35	62.82939	10770.04	61.73279	10409.59	59.66674
Feb	15807.89	10561.61	66.81227	10749.48	68.00072	11151.95	70.5467	9887.365	62.54702	9735.824	61.58838	9450.299	59.78216
Mar	14731.51	9826.553	66.70432	9984.365	67.77557	10322.11	70.06827	9259.376	62.85423	9131.688	61.98746	8890.844	60.35257
Apr	14534.6	9714.531	66.8373	9875.059	67.94175	10217.8	70.29984	9134.055	62.84355	9002.64	61.93939	8753.944	60.22833
May	14782.09	9878.371	66.82662	10061.64	68.06644	10451.96	70.70692	9212.738	62.32365	9061.296	61.29915	8773.836	59.35451

Jun	15684.58	10612.8	67.66391	10828.17	69.03704	11286.45	71.95889	9830.027	62.6732	9651.824	61.53703	9313.564	59.38039
Jul	17342.55	11983.85	69.10085	12254.02	70.65874	12829.3	73.97587	11003.26	63.44661	10780.38	62.16146	10357.83	59.72497
Aug	19346.86	13656.75	70.58898	13992.81	72.32601	14709.51	76.03047	12440.59	64.30289	12165.05	62.87866	11643.73	60.18408
Sep	20699.35	14727.17	71.14798	15114.82	73.02073	15943.19	77.02267	13329.11	64.39386	13013.41	62.86868	12417.18	59.98826
Oct	21544.33	15355.22	71.27265	15774.13	73.21705	16671.01	77.38003	13849.2	64.28231	13510.26	62.70913	12871.39	59.74375
Nov	20889.03	14730.86	70.51962	15107.95	72.32481	15915.9	76.19262	13376.85	64.0377	13072.39	62.58019	12498.57	59.8332
Dec	19402.2	13451.45	69.32952	13759.91	70.91934	14420.58	74.32445	12344.14	63.62237	12095.22	62.33942	11626.17	59.92191

2-Scenario two

In this scenario the temperature is increase by 2 C^0 and rainfall are constant increase and decrease as in the scenario one. Also in this scenario the Sudd total annual inundation area decrease by 38 % up to 58.23% (nearly to heft of the flooding area is reduced)

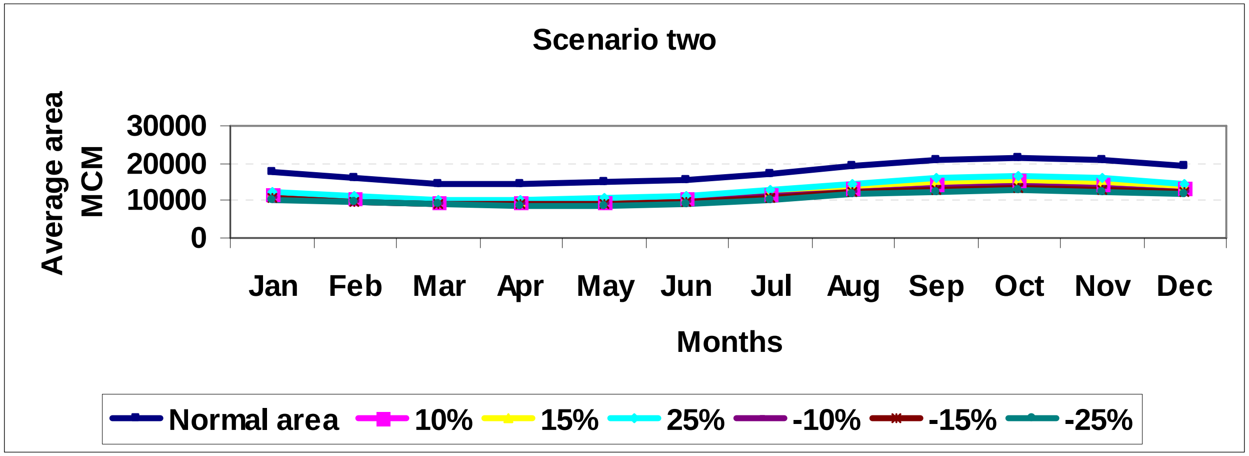

Figure6. 35: Scenario two average monthly areas

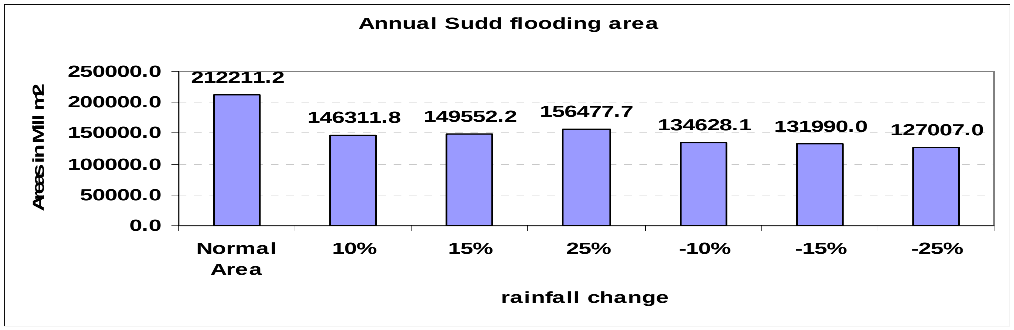

Figure6. 36: Scenario two change in annual area

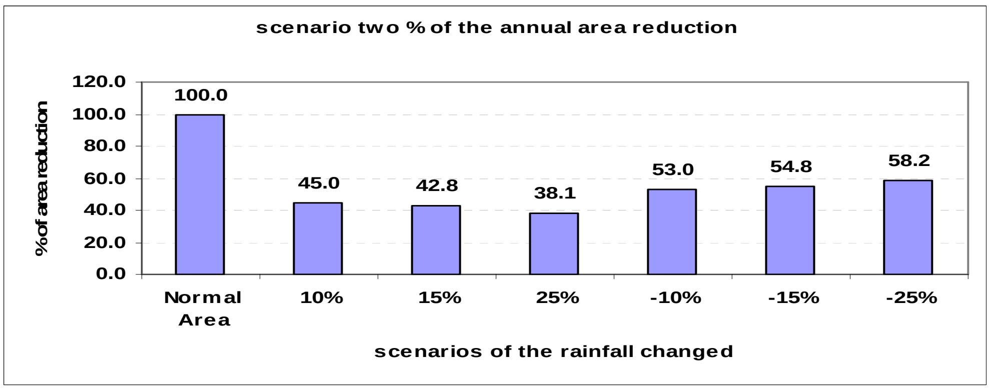

Figure6. 37: Percentage reduction of annual area result from scenario two

2- Scenarios three

In this scenario the temperature was increase by 3 degree while also the rainfall is still same increase and decrease as in the pervious two scenarios. Here the decrease in the area is observed from 69.7 % up to 86.8 % for the total annual area , here also around 13.2% from the annual area is only remain , which is 27997 Mill m^2 , which also less than average monthly permanent swamp.

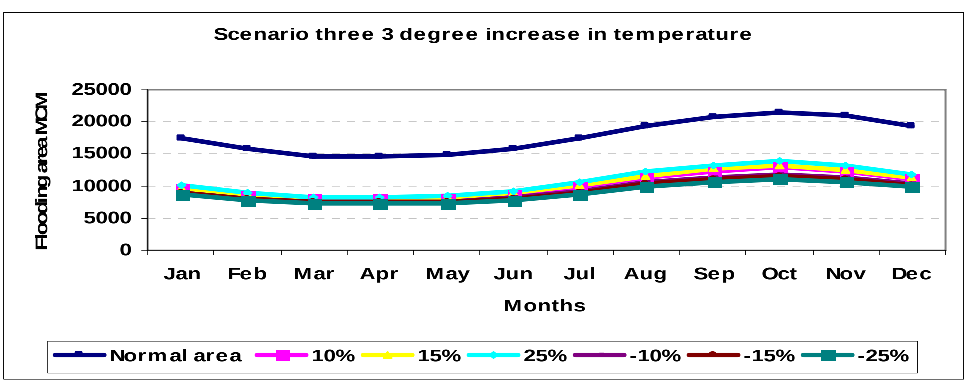

Figure6. 38: Scenario three average monthly areas

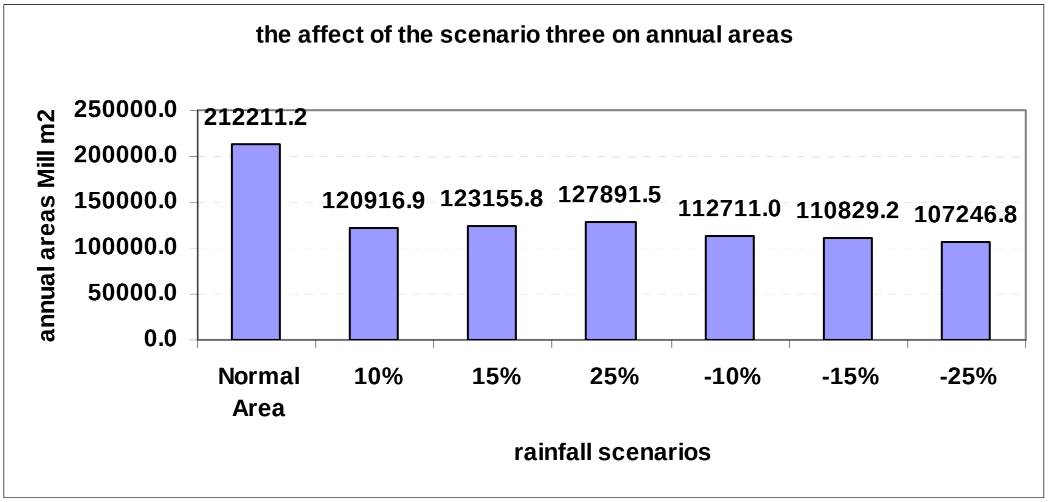

Figure6. 39: Scenario three change in annual area

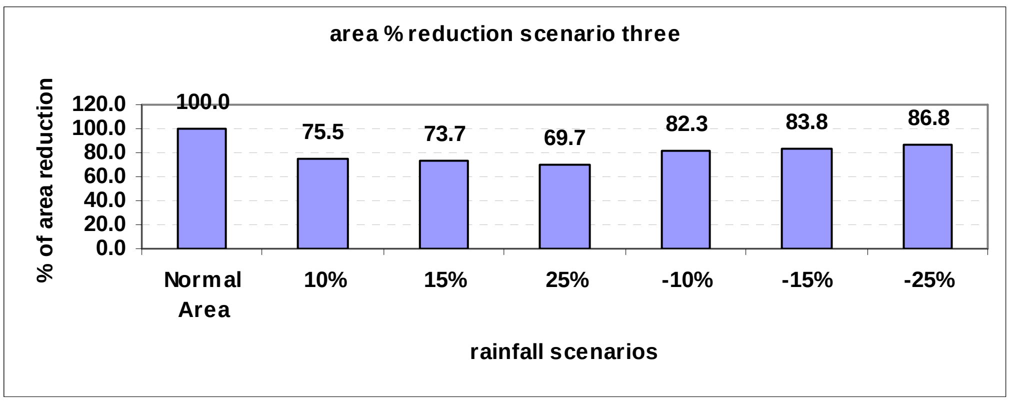

Figure6. 40: Percentage reduction of annual area result from scenario three

Here in the scenario three is the worst scenario, where the temperature is increase by 3 degree and the rainfall in decrease by 10%, 15% and 25%.where the reduction in the inundation area is reach 86.8% .

Table6. 11: Sudd average monthly percentage change from scenario three

3 degree increase in temperature													
Months	**Normal Area**	**increase in rainfall**						**decrease in rainfall**					
		10%	**% area**	**15%**	**%area**	**25%**	**%area**	**10%**	**% area**	**15%**	**%area**	**25%**	**%area**
Jan	17446.22	9607.402	55.06868	9763.479	55.96329	10094.58	57.86113	9038.164	51.80586	8908.236	51.06112	8661.586	49.64735
Feb	15807.89	8572.671	54.23033	8692.739	54.98988	8947.439	56.60109	8134.7	51.45974	8034.716	50.82725	7844.885	49.62639
Mar	14731.51	8012.718	54.3917	8111.95	55.0653	8322.198	56.4925	7649.953	51.92918	7566.951	51.36575	7409.146	50.29455
Apr	14534.6	7939.309	54.62353	8042.325	55.33229	8259.843	56.82885	7560.508	52.01733	7473.291	51.41727	7306.7	50.2711
May	14782.09	8061.7	54.53694	8183	55.35754	8438.48	57.08584	7613.214	51.50297	7509.448	50.80099	7310.748	49.4568
Jun	15684.58	8712.678	55.54933	8859.016	56.48233	9167.008	58.446	8171.539	52.09919	8046.317	51.30082	7806.57	49.77227
Jul	17342.55	9934.934	57.28648	10123.87	58.37594	10521.86	60.67082	9237.657	53.26587	9076.649	52.33746	8768.842	50.5626
Aug	19346.86	11430.01	59.07941	11670.41	60.322	12177.77	62.94442	10545.97	54.50999	10342.6	53.45882	9954.73	51.45398
Sep	20699.35	12350.18	59.6646	12630.29	61.01782	13222.74	63.87996	11323.41	54.70419	11088.14	53.56757	10640.52	51.40511
Oct	21544.33	12866.86	59.7227	13169.95	61.12955	13812.32	64.11113	11759.59	54.58322	11506.62	53.40906	11026.34	51.17978
Nov	20889.03	12285.33	58.81236	12552.94	60.09346	13120.49	62.81044	11308.88	54.1379	11085.89	53.07042	10662.57	51.04389
Dec	19402.2	11143.13	57.43231	11355.77	58.52827	11806.8	60.85291	10367.43	53.43433	10190.34	52.5216	9854.173	50.78896

6.4. 6 the impact of abstraction scenarios on Sudd area

The abstraction scenarios is to assessed the impact of the human activities on the swamp inundation area , for example the irrigation activities , water supply or water used for industry at upstream of the swamp area , also the scenario can be apply in downstream , if the swamp water can be trained . The results of the scenario are in the table 6.12, the abstracted water or diversion of the water from upstream by 10%, 25%, 35% and 50% was present in this scenario, it was shown that the swamp area reduction is highly sensitivity for any abstraction of the water, 10% abstraction is reduce the area of swamp for about. 55 % of total annual area while 50% is reduces the area for around 92.6 % also of annual area. The impacts for the season or monthly are also show in the table 6.12.

Table6. 12: Abstraction scenario

Abstraction Scenarios					
Months	**Normal Area**	**abstr 10%**	**abstr 25%**	**abstr 35%**	**abstr 50%**
Jan	17446.22	7529.165	5038.821	2834.091	1033.771
Feb	15807.89	6805.188	4524.668	2491.195	868.0883
Mar	14731.51	6459.391	4338.758	2455.615	987.841
Apr	14534.6	6368.331	4251.779	2405.293	958.1946
May	14782.09	6356.044	4259.751	2460.74	998.682
Jun	15684.58	6792.016	4564.114	2705.289	1152.101
Jul	17342.55	7645.183	5167.429	3148.365	1401.674
Aug	19346.86	8704.986	5952.755	3693.646	1726.833
Sep	20699.35	9311.147	6376.13	3964.009	1844.664
Oct	21544.33	9647.495	6605.561	4060.425	1848.317
Nov	20889.03	9305.842	6328.386	3763.094	1587.331
Dec	19402.2	8580.181	5784.899	3343.849	1307.208
total	212211.2	93504.97	63193.05	37325.61	15714.7
Decrease in area		**118706.2**	**149018.1**	**174885.6**	**196496.5**
% decrease in area		**55.93778**	**70.22162**	**82.4111**	**92.59478**

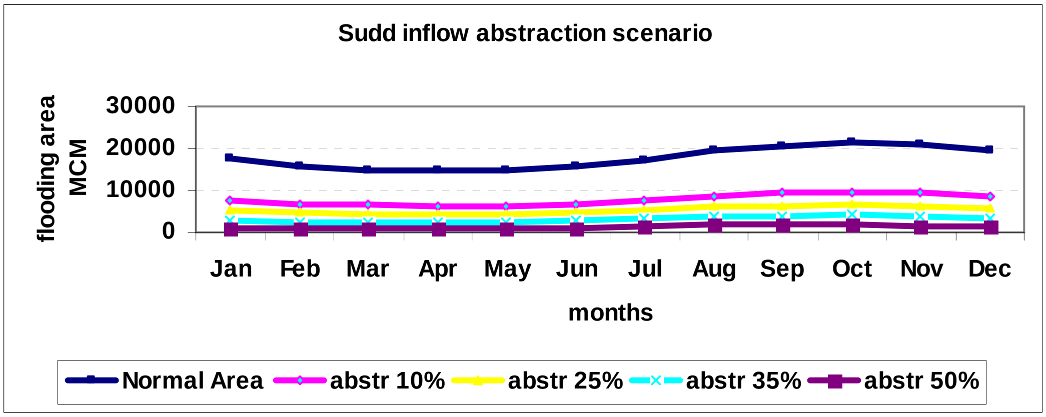

Figure6. 41: Abstraction scenario

Table6. 13 : Average monthly abstraction scenario impact

Months	Normal Area	inflow scenario abstraction							
		10 %	% area	25%	% area	35%	%area	50%	%area
Jan	17446.22	7529.165	43.15643	5038.821	28.88202	2834.091	16.24473	1033.771	5.925472
Feb	15807.89	6805.188	43.04931	4524.668	28.62285	2491.195	15.75919	868.0883	5.491487
Mar	14731.51	6459.391	43.84745	4338.758	29.45223	2455.615	16.66914	987.841	6.705634
Apr	14534.6	6368.331	43.81498	4251.779	29.25282	2405.293	16.54875	958.1946	6.59251
May	14782.09	6356.044	42.99828	4259.751	28.81697	2460.74	16.64676	998.682	6.756027
Jun	15684.58	6792.016	43.30379	4564.114	29.09937	2705.289	17.24808	1152.101	7.345437
Jul	17342.55	7645.183	44.0834	5167.429	29.79625	3148.365	18.15399	1401.674	8.082284
Aug	19346.86	8704.986	44.99431	5952.755	30.76858	3693.646	19.09171	1726.833	8.925652
Sep	20699.35	9311.147	44.9828	6376.13	30.80353	3964.009	19.1504	1844.664	8.911698
Oct	21544.33	9647.495	44.77973	6605.561	30.66032	4060.425	18.84684	1848.317	8.579131
Nov	20889.03	9305.842	44.54895	6328.386	30.29526	3763.094	18.01469	1587.331	7.598873
Dec	19402.2	8580.181	44.22273	5784.899	29.81569	3343.849	17.23439	1307.208	6.737425

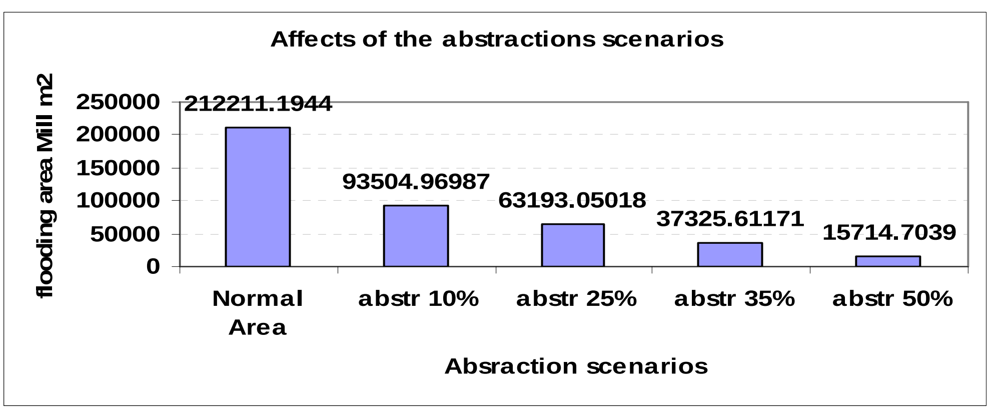

Figure6. 42: Affects of abstraction scenarios on the annual flooding areas

Abstraction or diversion of 50% of the river inflow into Sudd swamp is reducing the swamp annual area from 212211.19 Mill m^2 to 15714.7 Mill m^2, which is 92.6 % of the normal areas is reduced.

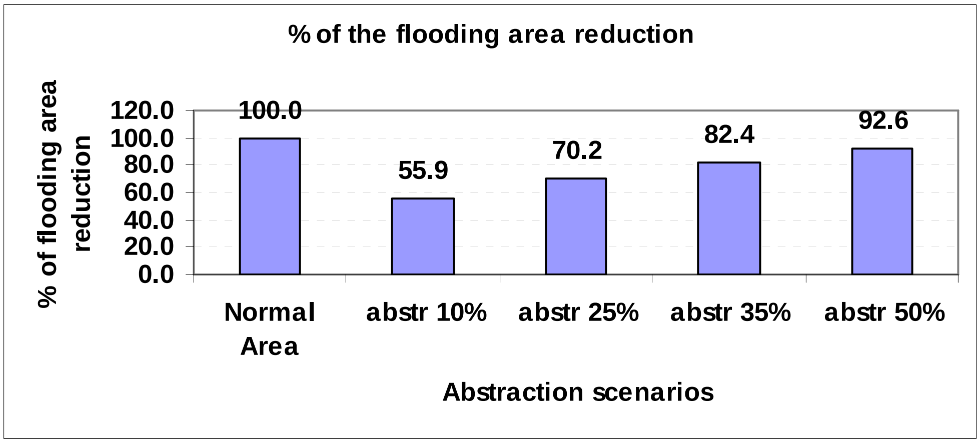

Figure6. 43: Percentage reduction of annual flooding area result from abstraction scenarios

CHAPTER SEVEN

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions:

The reservoir water balance model has been developed, using measured inflows and predicted outflows, and tested by its ability to reproduce areas of flooding over the period of 1950-2009. The model efficiency shows poor results of R^2 = 0.3813 for the monthly outflows data correlation estimated and measured, which indicted the addition ungauged inflow torrents errors, also the average monthly outflows correlation resulted of R^2 = 0.8363, which is quite good due to reduction on the cumulated errors on the measured time series, also the result of R^2 = 0.5277 was obtained for annual outflows correlations. After correction of the errors, the model efficiency shows the results of 35, -0.0003 and -0.004 of the Nash and Sutcliffe, Relative Error and Bias respectively.

The average aerial evaporation was estimate using Thronthwaite method which was found as 1706 mm/yr that is substantially less than the 2150 mm/yr used in earlier studies (Sutcliffe) and high than 1636 mm/yr of (Mohammed). These differences can be explained by the inclusion of larger areas not permanently saturated throughout the year and addition to the methods use to estimate the model inputs parameters. Also Hamon method was used for the reasons of comparative of the two results from models, which resulted of 1395 mm /yr.

The average monthly inundation area from 1950 to 2009 of the Sudd area has been found as 17684.3 Million m^2 with mean volume of 249660.2 Million m^3, this result is about 84 % of Mohammed 2004, 187 % of Sutcliffe 1905-1961, 80% of Sutcliffe 1961-1980 and 138 % of the Sutcliffe 1905-1980. The different between results can be explained as methodologies apply for estimated the inputs as the evaporation, aerial rainfall and inflow torrents.

The investigations were made for prediction of the Sudd outflow and Sudd inundation area by using the inflow to Sudd swamp area, the correlation coefficient R^2 was obtained as 0.773 and 0.6618 for the outflow and flooding area respectively.

Also the results of the dynamics of the Sudd area inundation, led to classify the three flooding zones, which are occasional, permanent and seasonal zones.

The water balance of the three sub-basins was estimated , and result of missing of inflow of dv/dt = -137553 MCM/yr for Bahr el Jebel basin , dv/dt = -77174 .26 MCM/yr for Bahr el Ghazal basin and dv/dt = 1742.83 MCM/yr for Sobat basin which is missing from outflows, this results led to estimated the total outflows of the three sub-basin at Malakal station as 31958.53 MCM/yr .

The model results can be used to estimate what the effect of the climate change and human activities would have been during the period 1950-2009 by using the measured Mongalla inflows and rainfall series to model the flooded areas with different numbers of the scenarios. The temperature increase over swamp region and the canal diversions are subtracted from upstream the swamp area, flows to give residual river inflows, and swamp outflows were estimated from these; the flooded areas are then recalculated and compared with estimates area without any change.

Different climate change and abstraction scenarios were tested. Constant increase in temperature 1 , 2, and 3 degree and increase and decrease in rainfall by 10%,15%25% were assumed . And results show the great impact on the area reduction. Similarly impacts of a river abstraction of scenarios 10%.15% 25% 35% and 50% were identified, also reduced in periods of low natu ral flows. To indicate the effect of varying abstractions flows, diversions were tested. Each trial provided monthly flooded areas for 1950-2009 which may be compared with natural conditions of the normal estimate area by model without any change.

The results on the scenarios shows that the timing of seasonal fluctuations would remain with the amplitude reduced. Presentation of results requires a choice of the important features. The effects of the changes could be presented in terms of averages. A reduction in average swamps of 55% -92 % and in swamps area for the abstraction change and of 73%-86% of the swamps area is estimated for the climate change effect. Seasonal variations in canal diversions could weight the reduction to permanent or seasonal swamps.

However, presentation of the natural regime shows that areas of flooding have varied greatly with river regime, with the permanent swamps varying more than the seasonal swamps.
The effects would be relatively greater in the early years of low inflows than in the recent years of high flows; indeed, the effect of the abstraction on the areas of maximum flooding would be less than the changes which occurred when Lake Victoria rose in 1961-1964.

7.2. Recommendation

- More detailed resource assessment on water balance, sustainable abstractions and the special variability of water quality and quantity should be done. Particularly, the potential impact of large-scale water abstraction for production upstream the swamp area , regional hydrology of the Sudd area should be assessed in detail, with special attention to the impacts of rural drinking water, flooding zones, livestock watering , grassland , small scale irrigation, equitable water utilization and swamp sustainability.
- More hydrological stations need to be established, especially upstream Bahr el Ghazal confluence with the White Nile, so that the Bahr el Ghazal contribution to White Nile can be measured, those also assist to quantify the torrents inflow to Sudd swamp. Moreover, Investigations of groundwater flux and directions are very important to improve the results obtained and issues identified.
- Great attention should be paid for the swamp ecosystem, before any project is proposed for utilization of the swamp water.

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APPENDIXES

Appendix A: Hydrological data
Appendix A. 1: White Nile river flow gauged at Malakal station MCM/MON

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	3080	1790	1480	1420	1710	1960	2430	2820	3090	3430	3300	3080	29590
1951	2210	1446	1350	1170	1190	1630	2110	2340	2470	2690	2650	2620	23876
1952	1780	1315	1220	1190	1420	1730	2190	2470	2570	2780	2750	2570	23985
1953	624	521	478	482	534	675	821	971	1069	1135	1146	915	9370
1954	1710	1250	1290	1290	1360	1780	2320	2770	3130	3490	3360	3220	26970
1955	2610	1590	1400	1400	1500	1930	2350	2590	2790	3090	3040	3090	27380
1956	2840	2040	1580	1540	1820	2090	2480	2750	2990	3320	3180	3240	29870
1957	3040	1780	1650	1790	1600	2060	2450	2740	2790	2960	2800	2340	28000
1958	1600	1290	1290	1180	1380	1750	2340	2670	2840	3110	2910	3010	25370
1959	2220	1360	1380	1240	1560	1910	2300	2530	2680	2920	2860	2940	25900
1960	2320	1481	1400	1320	1610	1950	2390	2650	2680	2840	2780	2730	26151
1961	1820	1320	1380	1380	1380	1730	2310	2850	3220	3730	3430	3400	27950
1962	3300	2700	2420	1810	1900	2260	2740	3060	3250	3530	3500	3730	34200
1963	3760	2950	2270	1880	2350	2610	3030	3460	3890	4630	4670	4750	40250
1964	3930	3211	2890	2480	2440	2560	3160	4160	5210	6090	6210	6430	48771
1965	6060	4470	3800	3070	2800	2750	3500	4040	4190	4570	4400	4130	47780
1966	3210	2320	2190	1990	2320	2790	3250	3610	3940	4420	4520	4390	38950
1967	3560	2390	2140	1900	1870	2170	2750	3250	3560	4220	4090	4050	35950
1968	3720	2776	2260	1850	1890	2220	2710	3100	3330	3680	3710	3260	34506
1969	2590	2080	2190	2040	2130	2510	3070	3300	3440	3820	3870	3800	34840
1970	2810	2140	2170	1930	1970	2370	2860	3250	3560	3980	3990	4140	35170
1971	3470	2410	2370	2070	1990	2180	2780	3270	3580	3980	3960	4080	36140
1972	3260	2330	2070	1840	2310	2450	3020	3270	3210	3320	3020	2490	32590
1973	2040	1620	1690	1580	1920	2280	2690	2980	3150	3390	3370	3300	30010
1974	2440	1730	1740	1610	1770	2250	2750	3120	3530	4050	3860	3830	32680
1975	2640	1820	1850	1720	1820	2140	2650	3000	3350	3910	3980	3990	32870

1976	3650	2496	2060	1850	1950	2360	2760	3030	3150	3450	3460	3320	33536
1977	2350	1770	1860	1740	1710	2160	2770	3070	3350	3540	3510	3460	31290
1978	2840	1820	1860	1780	2190	2470	2840	3110	3230	3530	3500	3530	32700
1979	3090	2320	2200	1940	2100	2460	2980	3350	3510	3750	3590	2870	34160
1980	2290	1890	1890	1770	1910	2420	2770	3120	3240	3540	3520	3040	31400
1981	2120	1680	1760	1910	1910	2160	2560	2970	3290	3750	3430	3490	31030
1982	2220	1790	1830	1670	1740	1960	2360	2800	2970	3220	3130	2510	28200
1983	2005	1625	1699	1596	1667	1833	2344	2763	3006	3360	3338	3477	28713
1984	3007	1970	1790	1630	1713	2015	2518	2843	2928	3126	2777	2139	28456
1985	1784	1490	1548	1530	1732	2082	2565	2842	2942	3171	3125	2795	27606
1986	1934	1528	1621	1538	1580	1687	2311	2662	2780	3002	2723	2006	25372
1987	1699	1439	1542	1466	1543	1907	2343	2679	2807	2974	2903	2602	25904
1988	1864	1551	1612	1459	1571	2020	2588	2960	3221	3706	3600	3772	29924
1989	3622	2162	1788	1652	1753	2028	2499	2903	3079	3327	3267	3052	31132
1990	2386	1736	1780	1622	1723	1976	2571	2944	3019	3217	3182	2923	29079
1991	1521	1299	1500	1679	1637	2354	2874	3289	3457	3764	3733	3756	30863
1992	2943	2097	1879	1688	1922	2115	2642	2999	3181	3463	3460	3610	31999
1993	3493	2519	2083	1840	2042	2363	2891	3203	3262	3489	3395	3246	33826
1994	2203	1671	1699	1568	1774	2172	2718	3146	3398	3644	3520	3322	30835
1995	2491	1714	1700	1642	1789	1998	2604	2982	3173	3454	3392	3209	30148
1996	2462	1917	1832	1790	2105	2526	2998	3351	3600	3919	3787	4001	34288
1997	3854	2591	2068	1844	2191	2507	2942	3225	3246	3419	3396	3442	34725
1998	1105	881	815	758	760	882	1067	1197	1294	1362	1382	1376	12878
1999	3583	2339	2017	1780	2225	2721	3174	3441	3477	3797	3690	3777	36021
2000	3531	2342	1988	1784	2075	2504	2985	3258	3320	3541	3430	3485	34243
2001	2589	1806	1822	1725	1846	2307	2826	3217	3408	3624	3506	3576	32252
2002	3852	2058	1877	1768	1776	2018	2673	3033	3133	3359	3193	2508	31248
2003	1521	1299	1500	1679	1637	2354	2874	3289	3457	3764	3733	3756	30863
2004	2386	1736	1780	1622	1723	1976	2571	2944	3019	3217	3182	2923	29079
2005	1521	1299	1500	1679	1637	2354	2874	3289	3457	3764	3733	3756	30863
2006	2943	2097	1879	1688	1922	2115	2642	2999	3181	3463	3460	3610	31999
2007	3493	2519	2083	1840	2042	2363	2891	3203	3262	3489	3395	3246	33826
2008	2203	1671	1699	1568	1774	2172	2718	3146	3398	3644	3520	3322	30835
2009	3854	2591	2068	1844	2191	2507	2942	3225	3246	3419	3396	4001	35284

Total	161053	115844	108577	100111	108404	128581	158136	179503	190999	209343	204714	198433	1863697
Max	6060	4470	3800	3070	2800	2790	3500	4160	5210	6090	6210	6430	48771
Mean	2684	1931	1810	1669	1807	2143	2636	2992	3183	3489	3412	3307	31062
Stdev	898	610	465	356	364	376	424	483	555	667	685	798	5974

Appendix A. 2: Bahr el Jebel river flow gauged at Mongalla station MCM/MON

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	1630	1350	1410	1530	1660	1560	1880	2720	2580	2880	1710	1450	22360
1951	1350	1211	1190	1310	1510	1570	1510	1890	1450	1870	2120	2100	19081
1952	1870	1699	1680	1900	2400	2180	2420	3540	3180	3150	2400	2250	28669
1953	1990	1670	1690	1610	1910	1950	2130	2340	1880	1910	1900	1650	22630
1954	1510	1280	1380	1520	1910	1800	2020	2700	3010	2230	1870	1700	22930
1955	1640	1440	1510	1500	1740	1530	1690	2200	2870	3060	2370	1780	23330
1956	1620	1481	1490	1640	1950	1850	1940	2500	3060	3010	2100	1860	24501
1957	1780	1570	1780	1940	2380	2690	2170	2480	2090	2080	1960	1910	24830
1958	1810	1570	1700	1730	2080	2100	2770	2870	2520	2470	1940	1880	25440
1959	1760	1490	1580	1550	2120	1910	1900	2440	2390	2220	2030	1820	23210
1960	1630	1543	1680	1830	2090	1860	2210	2500	2640	2780	2350	2040	25153
1961	1900	1630	1770	1790	2010	2040	2590	3550	3730	4250	4730	4080	34070
1962	3450	3030	3560	3660	4330	4080	4710	4890	5000	5040	4520	4360	50630
1963	4420	3890	4280	4790	6050	5640	5500	5540	5310	4980	5010	5070	60480
1964	4390	3874	3860	4510	5290	4940	5720	6320	6860	7340	5760	5270	64134
1965	5260	4530	4780	4570	4740	4430	4580	4810	4440	5040	4900	4840	56920
1966	4290	3780	4130	4130	4360	4060	4250	4510	4680	4730	4730	4310	51960
1967	3990	3410	3610	3370	3780	3710	4070	5080	4790	5010	5120	4560	50500
1968	3720	3304	3500	3480	4040	4150	4550	5120	4610	4780	4610	4660	50524
1969	4310	3790	4320	4030	4640	4330	4600	5370	5030	4530	4410	4350	53710
1970	4080	3450	3710	3790	4190	4210	4550	5760	6600	6200	5240	4550	56330
1971	4400	3770	4040	3900	4210	3970	4220	4550	4920	4890	4150	3840	50860
1972	3620	3459	3280	3040	3330	3400	3500	3690	3570	3970	4320	4270	43449
1973	3850	3310	3350	3250	3960	3620	3680	4270	4130	4030	3970	3850	45270
1974	3690	3180	3410	3360	3600	3680	4190	4510	4390	4350	3900	3740	46000
1975	3530	3060	3280	3190	3440	3450	3430	4690	5000	4820	4170	4100	46160

1976	3860	3635	3670	3580	3850	3860	4090	4420	4420	4000	3810	3760	46955
1977	3610	3140	3370	3430	3710	3550	4110	4480	4250	4490	4300	4390	46830
1978	3340	2390	3110	3130	3370	3360	3550	4860	4690	5040	4590	4390	45820
1979	4420	4020	4340	4380	4710	4580	4660	4590	4370	4450	4270	4310	53100
1980	4120	3680	3780	3590	3770	3700	3890	3940	3860	4020	3850	3930	46130
1981	3840	3360	3630	3390	3470	3330	3430	3670	3580	3730	3730	3460	42620
1982	3090	2680	2920	2770	2820	2890	3220	3450	3580	3920	3990	3780	39110
1983	2926	2551	2836	2834	2923	2990	3428	3586	3499	3598	3524	3804	38499
1984	3531	2808	3104	3047	3309	3505	3779	3963	3914	3942	3397	2864	41163
1985	2728	2374	2666	2709	2855	3070	3407	3441	3275	3361	3354	3204	36442
1986	2708	2549	2830	2869	2945	2849	3363	3475	3344	3292	2915	2498	35638
1987	2531	2162	2466	2470	2553	2829	3121	3240	3052	3059	3073	2941	33498
1988	2520	2402	2601	2615	2790	3008	3391	3628	3614	3849	3722	4116	38255
1989	4086	2963	3417	3359	3605	3840	4030	4218	4260	4343	3977	3629	45727
1990	3177	2740	3073	3012	3233	3304	3732	3906	3756	3753	3592	3438	40715
1991	2407	2514	2669	2988	2959	3407	3609	4086	3923	3900	3860	4162	40486
1992	3687	3274	3504	3564	3897	3828	4211	4351	4286	4333	4071	4175	47179
1993	4156	3381	3540	3529	3844	4053	4384	4476	4447	4645	4352	4127	48934
1994	3254	3006	3234	3226	3487	3533	3877	4171	4098	4077	3883	3838	43684
1995	3332	2890	3239	3268	3510	3523	3949	4084	4023	4015	3765	3691	43287
1996	3258	2960	3146	3290	3645	3836	4184	4430	4424	4553	4359	4674	46757
1997	4653	3727	3975	3913	4344	4496	4714	4756	4664	4811	4493	4316	52861
1998	3909	3313	3790	3635	3859	3895	4234	4422	4409	4520	4308	4473	48767
1999	4471	3377	3737	3600	4162	4422	4627	4754	4701	4992	4667	4651	52162
2000	4476	3558	3948	3846	4176	4361	4556	4645	4578	4707	4373	4316	51540
2001	3538	3127	3491	3458	3671	3831	4050	4356	4300	4277	4045	4191	46337
2002	4572	2956	3748	3509	3718	3966	4184	4227	4338	4404	3956	3251	46828
2003	2639	2485	2753	3014	2916	3451	3668	4034	3829	3830	3860	4162	40640
2004	3687	3274	3504	3564	3897	3828	4211	4351	4286	4333	4071	4175	47179
2005	4156	3381	3540	3529	3844	4053	4384	4476	4447	4645	4352	4127	48934
2006	3254	3006	3234	3226	3487	3533	3877	4171	4098	4077	3883	3838	43684
2007	3332	2890	3239	3268	3510	3523	3949	4084	4023	4015	3765	3691	43287
2008	3258	2960	3146	3290	3645	3836	4184	4430	4424	4553	4359	4674	46757
2009	4653	3727	3975	3913	4344	4496	4714	4756	4664	4811	4493	4674	53219

Total	198669	171031	185195	185735	204548	205243	221543	242761	240158	243966	227299	220009	2546158
Max	5260	4530	4780	4790	6050	5640	5720	6320	6860	7340	5760	5270	64134
Min	1350	1211	1190	1310	1510	1530	1510	1890	1450	1870	1710	1450	19081
Mean	3311	2851	3087	3096	3409	3421	3692	4046	4003	4066	3788	3667	42436
Stdev	1000	821	887	856	940	915	951	918	978	994	960	1001	10665
CV	30	29	29	28	28	27	26	23	24	24	25	27	25

Appendix A. 3: Sobat river flow gauged at Hilleit Dollib station MCM/MON

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	1790	390	170	250	580	870	1290	1680	1900	2110	2080	2040	15150
1951	810	182	140	110	150	660	1090	1290	1470	1680	1680	1630	10892
1952	610	249	160	160	330	710	1170	1410	1540	1690	1700	1310	11039
1953	330	110	70	120	320	660	1100	1450	1690	1770	1780	1190	10590
1954	390	170	140	190	240	690	1120	1450	1700	1980	1980	1950	12000
1955	1310	400	220	310	380	920	1310	1510	1610	1830	1900	1950	13650
1956	1640	808	330	410	710	1040	1380	1650	1920	2160	2110	2160	16318
1957	1980	500	400	660	380	970	1360	1630	1710	1880	1780	1040	14290
1958	310	170	110	100	300	720	1280	1570	1770	2030	1960	1960	12280
1959	980	260	190	90	400	840	1170	1370	1560	1780	1770	1800	12210
1960	1080	321	220	170	440	830	1240	1490	1570	1730	1730	1640	12461
1961	640	280	220	400	310	670	1260	1620	1880	2160	2170	2240	13850
1962	2220	1780	1260	520	690	1070	1480	1800	1980	2160	2140	2260	19360
1963	2300	1340	490	410	880	1100	1430	1710	1870	2090	2090	1890	17600
1964	1410	974	620	430	530	940	1350	1680	1980	2310	2340	2380	16944
1965	1950	970	280	380	500	660	1310	1710	1810	1940	1940	1850	15300
1966	1930	970	700	690	1160	1480	1830	2030	1870	2010	1970	1980	18620
1967	2260	1360	710	480	280	350	720	1250	1650	1920	1900	1960	14840
1968	1470	715	250	70	160	750	1280	1530	1640	1800	1750	1400	12815
1969	710	400	360	300	390	860	1430	1600	1700	1880	1860	1360	12850
1970	460	230	230	190	270	850	1270	1530	1720	1930	1960	2010	12650
1971	2230	1340	870	580	470	630	1120	1720	2160	2350	2320	2380	18170
1972	1050	456	130	194	270	740	1130	1430	1560	1690	1410	790	10849
1973	340	170	100	120	360	930	1330	1550	1730	1890	1920	1450	11890
1974	550	220	130	70	290	1030	1520	1730	1870	2120	1800	1650	12980
1975	380	410	210	110	360	810	1330	1690	2030	2240	2220	2320	14110
1976	530	383	320	280	340	690	1330	1680	1880	2090	2000	1430	12953
1977	610	250	130	110	140	460	1020	1500	1690	1850	1920	1820	11500
1978	890	230	190	230	730	1030	1420	1560	1630	1800	1850	1800	13360
1979	1190	640	670	640	650	750	1250	1620	1650	1670	1570	650	12950
1980	981	754	685	619	699	1101	1337	1597	1709	1908	1916	1537	14843
1981	855	598	588	722	699	908	1181	1485	1746	2064	1850	1871	14568
1982	929	680	640	544	573	760	1033	1359	1509	1671	1627	1144	12470
1983	770	557	543	490	519	665	1021	1332	1535	1775	1781	1861	12850
1984	1513	813	610	515	553	800	1150	1391	1477	1601	1365	869	12660
1985	606	457	431	441	567	850	1185	1391	1488	1634	1624	1356	12029
1986	717	485	485	447	455	557	997	1257	1368	1509	1325	771	10372
1987	543	419	426	393	427	720	1020	1270	1388	1488	1459	1213	10767
1988	665	503	478	388	448	804	1202	1478	1695	2031	1976	2080	13748
1989	1969	956	609	531	583	810	1136	1436	1589	1750	1729	1546	14644
1990	1052	640	603	509	561	771	1190	1466	1545	1669	1666	1451	13122
1991	411	316	395	551	497	1052	1414	1722	1870	2074	2074	2068	14445
1992	1465	907	676	558	708	875	1242	1507	1665	1851	1872	1960	15287
1993	1873	1220	828	671	797	1058	1427	1658	1725	1870	1824	1690	16642
1994	917	591	543	469	598	917	1299	1616	1826	1985	1916	1746	14424

1995	1130	623	544	524	610	788	1214	1494	1659	1844	1822	1663	13914
1996	1109	774	641	633	844	1179	1506	1768	1976	2189	2114	2250	16985
1997	2141	1274	816	674	908	1165	1465	1675	1713	1818	1824	1835	17309
1998	1478	933	902	763	792	1001	1402	1660	1793	1988	1962	2016	16690
1999	1940	1087	779	626	933	1324	1637	1835	1885	2099	2043	2084	18270
2000	1901	1089	757	629	822	1163	1497	1699	1768	1909	1850	1867	16951
2001	1203	692	634	585	652	1017	1379	1669	1833	1970	1906	1935	15475
2002	2140	878	675	617	600	803	1265	1532	1629	1774	1674	1143	14730
2003	411	316	395	551	497	1052	1414	1722	1870	2074	2074	2068	14445
2004	1465	907	676	558	708	875	1242	1507	1665	1851	1872	1960	15287
2005	1873	1220	828	671	797	1058	1427	1658	1725	1870	1824	1690	16642
2006	917	591	543	469	598	917	1299	1616	1826	1985	1916	1746	14424
2007	1130	623	544	524	610	788	1214	1494	1659	1844	1822	1663	13914
2008	1109	774	641	633	844	1179	1506	1768	1976	2189	2114	2250	16985
2009	2141	1274	816	674	908	1165	1465	1675	1713	1818	1824	2250	17723
Total	71705	39631	28752	25751	32818	52831	77085	94177	103564	114646	112247	103875	857083
Max	2300	1780	1260	763	1160	1480	1830	2030	2160	2350	2340	2380	19360
Min	310	110	70	70	140	350	720	1250	1368	1488	1325	650	10372
Mean	1195	661	479	429	547	881	1285	1570	1726	1911	1871	1731	14285
Stdev	612	380	260	203	222	206	177	155	163	192	209	419	2247
CV	51	58	54	47	41	23	14	10	9	10	11	24	16

Appendix A. 4: Bahr el Ghazal river flow gauged at Lake No station MCM/MON

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	106	94	109	91	94	85	94	95	93	110	95	86	1151
1951	116	85	100	83	86	75	85	86	77	84	76	82	1036
1952	97	75	88	80	90	80	85	88	80	91	81	104	1038
1953	111	77	100	88	92	85	92	96	84	105	93	105	1128
1954	110	73	95	86	93	85	99	110	111	126	107	105	1200
1955	108	81	98	85	93	78	86	89	92	105	89	94	1099
1956	99	87	104	88	92	81	91	91	84	96	83	89	1085
1957	88	86	104	88	101	84	91	92	84	90	80	108	1095
1958	108	75	98	84	90	80	88	91	84	90	74	87	1048
1959	103	74	99	89	96	84	94	96	87	94	84	94	1095
1960	103	82	98	90	97	87	96	96	86	92	82	91	1099
1961	98	70	96	76	89	82	88	102	105	130	98	96	1131
1962	90	63	96	100	101	92	104	104	99	113	106	123	1190
1963	122	109	148	114	123	118	133	145	157	211	201	237	1817
1964	209	157	188	160	158	126	150	206	251	314	301	336	2556
1965	341	237	293	209	191	162	182	194	185	218	191	189	2592
1966	106	91	124	101	96	102	118	131	161	200	198	199	1628
1967	108	69	119	110	132	142	168	166	149	191	171	174	1697
1968	186	144	167	138	143	114	118	131	131	157	152	155	1738
1969	157	114	151	136	145	128	136	141	136	161	156	203	1763
1970	196	129	161	135	142	118	132	143	143	170	158	177	1803
1971	103	73	125	116	126	121	137	129	110	135	128	141	1444
1972	183	131	161	143	169	133	157	153	128	135	125	141	1759

1973	141	98	133	114	129	105	113	118	111	125	113	153	1453
1974	157	102	134	76	130	132	145	130	90	160	160	181	1598
1975	188	96	136	125	121	104	110	109	103	139	137	139	1505
1976	259	148	145	122	134	130	119	112	99	113	113	157	1651
1977	145	103	143	127	130	132	145	130	129	140	124	136	1584
1978	162	108	138	121	122	112	118	129	125	143	128	144	1550
1979	158	114	127	101	121	133	143	143	144	173	157	122	1637
1980	107	90	94	89	94	110	122	133	136	147	145	131	1397
1981	101	84	89	93	94	101	115	128	138	154	142	145	1385
1982	104	87	92	85	89	95	109	123	127	137	133	114	1294
1983	97	82	87	83	86	91	108	122	129	141	139	145	1311
1984	130	93	90	84	88	97	114	124	126	134	121	102	1302
1985	90	78	83	81	88	99	115	124	127	135	132	123	1275
1986	95	79	85	81	84	86	107	119	121	130	119	97	1203
1987	87	76	82	79	82	93	108	119	122	129	125	117	1220
1988	93	79	85	79	83	97	116	128	136	152	148	154	1350
1989	150	99	90	85	89	97	113	126	131	140	137	131	1389
1990	110	85	90	84	88	95	116	128	129	136	134	127	1322
1991	82	71	81	86	85	108	125	139	143	154	152	154	1380
1992	128	97	93	86	95	100	118	129	134	144	143	149	1417
1993	145	111	100	91	98	108	126	136	137	145	141	137	1476
1994	104	83	87	82	90	102	120	134	141	150	145	140	1379
1995	113	85	87	85	90	96	117	129	134	144	141	136	1357
1996	112	91	92	89	101	113	129	141	148	159	154	162	1491
1997	157	113	99	91	103	112	128	137	136	143	141	144	1505
1998	128	98	103	95	98	105	125	136	140	150	147	152	1478
1999	148	105	98	89	104	119	135	144	144	155	151	155	1547
2000	147	105	97	89	100	112	129	138	139	147	142	145	1489
2001	116	88	91	87	92	106	124	136	142	150	145	148	1425
2002	157	96	93	89	90	97	119	131	133	141	135	114	1392
2003	118	91	103	94	100	108	138	151	150	162	153	148	1516
2004	126	100	107	97	107	119	142	153	149	324	307	303	2033
2005	238	193	219	180	165	175	221	250	253	284	278	296	2753
2006	259	179	191	150	188	233	288	313	310	334	317	337	3098
2007	321	215	210	176	207	239	292	323	324	354	331	346	3337
2008	308	205	227	176	237	263	304	321	315	339	319	343	3357
2009	157	113	99	91	103	112	128	137	136	143	141	162	1523
Total	8483	6217	7123	6220	6747	6778	7766	8298	8247	9467	8920	9304	93570
Max	341	237	293	209	237	263	304	323	324	354	331	346	3357
Min	82	63	81	76	82	75	85	86	77	84	74	82	1036
Mean	141	104	119	104	112	113	129	138	137	158	149	155	1559
Stdev	59	37	42	30	33	37	45	50	53	63	61	66	527
CV	41	36	36	29	30	32	35	36	38	40	41	42	34

Appendix B 1: Metrological Data
Appendix B. 1: Bahr el Jebel Basin Aerial rainfall mm

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	6.0	0.3	7.7	99.9	110.1	177.8	165.5	177.5	110.0	131.6	3.3	0.1	989.8
1951	0.0	6.7	20.5	48.0	94.9	108.2	164.5	157.3	94.9	121.8	51.4	4.4	872.5
1952	0.0	0.8	14.3	45.5	125.7	107.4	130.3	181.7	146.0	135.2	24.9	0.9	912.9
1953	6.5	7.1	9.3	45.1	120.1	179.7	166.6	176.2	81.6	122.6	31.0	0.1	946.1
1954	0.0	7.4	21.4	57.6	124.0	134.2	187.6	150.4	165.8	98.2	11.7	2.3	960.7
1955	6.4	0.2	23.9	92.7	78.9	95.1	111.6	152.3	195.2	93.9	28.2	5.6	883.9
1956	1.6	6.1	37.0	52.3	71.2	132.2	142.5	233.1	136.4	137.2	17.6	5.2	972.4
1957	3.1	1.7	83.7	48.8	132.1	167.0	157.6	172.3	53.2	79.6	49.5	13.7	962.3
1958	1.7	4.1	9.8	56.5	76.2	184.0	148.6	99.8	152.5	91.9	8.8	8.4	842.0
1959	1.4	9.6	19.2	62.3	110.6	69.5	131.9	138.7	151.0	131.1	28.4	1.9	855.7
1960	6.1	2.9	22.7	104.0	64.7	77.0	136.7	123.8	130.4	123.8	12.2	7.3	811.6
1961	8.7	4.1	23.7	32.8	71.3	107.2	211.2	151.7	167.8	179.0	33.2	0.2	990.9
1962	1.4	0.5	37.9	46.2	110.3	131.0	130.1	138.9	156.0	125.5	18.7	2.7	899.3
1963	6.3	10.0	39.9	90.5	123.0	184.4	110.5	155.6	131.1	71.5	52.9	2.6	978.2
1964	0.0	5.1	21.0	58.4	158.6	87.1	187.3	183.7	157.3	123.3	17.1	6.7	1005.7
1965	0.0	2.0	12.0	82.3	79.7	77.5	96.0	159.9	143.1	98.5	21.9	2.8	775.6
1966	1.0	3.9	58.7	60.6	110.8	97.9	123.7	148.4	147.3	156.4	24.6	0.0	933.2
1967	0.0	7.4	15.2	15.8	99.4	125.4	177.5	161.5	160.7	114.0	40.0	0.2	916.9
1968	0.0	4.5	8.1	39.0	70.3	153.7	127.6	185.8	97.8	103.3	34.5	13.9	838.7
1969	3.2	16.7	62.5	49.7	100.0	99.2	115.2	146.6	121.3	88.0	21.6	6.1	830.1
1970	2.5	4.8	48.2	48.1	72.0	93.9	140.1	157.9	127.6	117.1	9.3	0.0	821.5
1971	0.1	2.2	14.1	28.7	162.3	49.8	144.8	183.6	114.3	94.5	15.1	0.8	810.3
1972	3.6	1.9	12.7	83.8	102.5	87.9	137.7	163.3	116.9	92.2	28.7	0.9	832.0
1973	0.0	5.2	6.8	55.9	113.4	90.6	132.5	162.5	144.9	114.9	13.6	2.7	843.0
1974	0.4	2.0	11.4	54.0	156.4	101.3	131.2	160.3	148.1	57.5	8.3	5.8	836.5
1975	0.1	0.8	8.8	40.8	148.5	146.1	112.9	233.8	147.4	102.3	27.2	1.4	970.1
1976	0.0	1.9	25.5	68.0	126.1	82.9	115.9	145.1	68.9	68.0	25.1	2.6	730.1
1977	1.0	1.1	24.7	42.4	100.0	138.3	105.5	173.7	105.9	81.2	15.5	9.4	798.8
1978	0.0	2.3	14.4	82.9	53.4	104.4	137.6	198.3	118.8	132.8	17.8	1.7	864.4
1979	4.0	13.9	12.6	69.8	138.2	163.4	147.7	107.6	116.5	81.9	36.3	0.7	892.7

1980	0.2	4.1	11.5	18.1	160.7	136.6	166.4	167.7	123.3	129.0	47.4	0.0	964.9
1981	0.0	7.6	19.5	34.7	103.6	172.0	173.0	213.6	160.6	72.9	40.7	2.3	1000.4
1982	6.0	0.0	8.5	41.0	105.9	146.9	88.2	107.7	111.1	110.5	14.3	2.1	742.3
1983	0.0	0.0	11.0	45.5	90.0	143.7	107.7	147.1	122.4	111.0	43.7	6.1	828.2
1984	0.0	0.0	6.2	80.9	119.1	94.4	176.8	86.6	99.6	44.3	41.1	6.1	755.1
1985	10.3	5.7	89.3	109.8	148.5	116.6	94.9	96.8	115.1	84.1	48.5	13.0	932.5
1986	7.5	38.4	40.7	88.7	77.9	137.3	141.6	106.5	109.5	105.1	29.4	6.6	889.3
1987	0.0	9.3	26.1	68.2	143.1	86.7	45.1	73.4	90.9	61.6	58.2	7.5	670.2
1988	8.4	13.9	24.8	68.2	123.5	119.6	176.5	156.5	172.9	93.0	44.1	36.8	1038.2
1989	0.0	5.7	83.3	65.1	117.1	127.9	142.0	129.2	112.8	83.8	86.4	9.3	962.6
1990	7.5	28.6	51.4	54.8	85.7	35.0	127.6	153.1	107.7	99.0	46.7	23.5	820.5
1991	23.5	31.9	11.2	102.7	113.2	108.4	153.7	145.7	80.9	125.2	59.9	20.9	977.1
1992	15.6	30.2	32.3	84.5	101.9	66.6	117.1	170.0	95.8	110.6	52.8	22.2	899.8
1993	12.3	26.5	57.5	124.0	94.3	104.5	116.4	47.2	98.8	59.8	45.9	16.1	803.4
1994	8.9	22.6	70.7	98.8	136.5	131.4	130.8	103.4	112.1	98.8	38.8	9.8	962.5
1995	7.7	16.3	70.4	56.7	131.4	50.1	119.9	72.1	122.1	113.5	33.7	8.2	802.1
1996	6.6	9.8	70.0	120.8	125.9	110.9	114.2	38.5	132.0	124.5	28.6	6.6	888.4
1997	5.7	0.0	21.8	125.0	73.5	65.3	91.2	78.6	64.4	166.4	82.7	31.1	805.7
1998	18.3	7.5	35.1	103.2	76.4	124.1	147.5	81.8	63.2	155.2	60.2	0.0	872.5
1999	0.0	1.5	29.4	130.2	109.9	159.0	115.5	139.3	135.8	145.0	28.6	0.0	994.1
2000	0.0	0.0	13.9	54.6	90.4	122.3	142.4	117.6	106.1	71.2	58.1	62.0	838.5
2001	0.0	6.6	45.1	28.8	62.1	130.0	112.7	139.3	144.8	108.7	74.6	82.1	935.0
2002	0.0	0.0	18.3	73.3	68.8	92.2	99.8	124.3	114.1	123.1	20.9	63.4	798.1
2003	6.6	18.3	0.0	44.7	97.5	167.8	173.6	104.1	115.7	76.1	115.6	7.5	927.6
2004	5.7	0.0	1.3	14.5	71.9	113.8	131.3	102.0	112.5	105.3	107.2	47.6	813.2
2005	7.5	0.0	0.0	7.3	102.6	116.6	95.5	162.7	85.0	96.8	26.9	46.1	747.1
2006	7.5	10.3	5.7	89.3	116.8	142.9	111.6	106.1	97.2	114.6	71.3	47.6	920.8
2007	13.0	5.7	15.5	113.8	126.5	135.5	169.3	132.8	139.9	83.4	53.5	0.0	988.9
2008	13.4	0.0	15.5	83.1	99.7	65.5	120.0	112.0	163.9	121.6	52.8	0.0	847.5
2009	54.6	35.6	17.4	131.6	56.2	60.4	116.0	147.5	139.4	79.4	56.1	18.3	912.4
Total	311.9	473.1	1630.7	4024.2	6335.6	6938.0	8046.8	8444.6	7358.6	6342.4	2297.1	714.0	52917.1
Mean	5.2	7.9	27.2	67.1	105.6	115.6	134.1	140.7	122.6	105.7	38.3	11.9	882.0
Stdev	8.3	9.6	22.4	30.7	27.9	36.0	29.7	40.6	29.6	27.5	23.5	17.8	81.8
CV	159.6	121.5	82.6	45.8	26.4	31.1	22.1	28.8	24.1	26.0	61.3	149.7	9.3

Appendix B. 2: Mean temperature at Juba station C^0

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	27.8	29.0	29.7	28.9	27.5	26.2	24.7	25.0	25.4	25.6	26.9	27.7	27.0
1951	27.8	28.1	30.3	30.0	28.3	26.9	25.5	25.6	26.8	26.4	26.9	25.9	27.4
1952	28.4	29.0	29.4	28.2	26.3	26.6	25.7	25.3	26.2	26.6	27.9	28.7	27.4
1953	28.5	29.8	30.3	29.5	28.2	26.8	25.5	25.4	26.8	27.7	27.4	26.8	27.7
1954	27.8	30.5	31.0	28.3	26.8	26.2	25.0	25.0	25.6	26.7	27.4	27.2	27.3
1955	28.6	29.0	29.8	29.0	27.4	26.7	25.5	24.9	25.2	26.8	26.9	26.9	27.2
1956	26.1	30.1	29.1	27.4	26.7	25.8	25.3	25.1	25.8	26.2	27.6	27.5	26.9
1957	27.2	27.4	28.5	27.8	27.6	26.5	26.1	25.6	27.0	27.8	27.8	27.9	27.3
1958	29.6	28.6	31.0	30.3	28.8	26.6	25.3	25.4	26.2	27.0	28.5	28.4	28.0
1959	28.9	28.5	30.2	29.6	27.5	26.8	25.9	25.4	26.2	26.7	27.0	27.3	27.5
1960	27.8	29.9	29.7	27.8	27.2	25.9	25.8	25.9	26.2	26.8	27.6	28.6	27.4
1961	29.2	27.9	29.6	29.0	28.3	26.9	25.3	25.1	26.0	25.8	25.3	25.3	27.0
1962	25.3	28.0	28.6	27.7	26.4	26.3	25.7	25.5	25.9	26.7	27.5	27.2	26.7
1963	27.8	28.3	28.9	27.4	27.1	26.6	25.6	25.9	27.4	28.0	26.8	27.3	27.3
1964	28.2	28.8	30.5	28.7	27.8	26.3	25.2	25.3	25.9	26.1	27.3	26.8	27.2
1965	27.6	28.9	30.8	28.6	27.6	26.8	25.3	26.2	26.8	26.5	27.1	27.2	27.5
1966	29.1	28.7	28.8	28.2	28.1	27.5	25.6	26.0	26.2	27.0	27.7	27.9	27.6
1967	28.1	29.2	29.3	30.3	28.2	26.7	25.2	25.2	25.9	26.3	25.8	26.5	27.2
1968	26.9	28.5	29.2	28.5	27.3	26.3	25.8	25.6	27.2	27.5	28.2	27.1	27.3
1969	27.9	29.0	29.2	29.9	28.2	27.2	24.7	26.3	26.9	27.8	27.7	28.7	27.8
1970	28.3	30.5	30.1	29.4	28.4	25.8	26.2	25.5	26.3	27.3	27.7	26.7	27.7
1971	27.3	28.8	31.1	29.1	27.2	26.7	25.5	26.2	25.9	27.6	27.4	26.3	27.4
1972	29.2	29.3	31.2	29.6	28.9	26.7	26.9	26.2	27.8	27.9	27.6	28.3	28.3
1973	29.4	31.4	31.7	29.3	28.0	27.0	26.1	25.9	26.8	28.2	28.2	28.4	28.4
1974	28.4	30.9	30.7	28.6	27.1	27.0	25.6	25.9	26.0	27.6	27.9	27.2	27.7
1975	28.2	30.5	30.4	29.5	28.3	26.2	26.0	25.4	26.2	27.2	28.0	27.6	27.8
1976	28.3	29.5	30.1	28.9	27.2	26.7	25.9	25.9	27.3	28.2	28.3	29.3	28.0
1977	28.7	30.1	30.3	29.4	28.6	27.0	26.2	26.4	26.6	28.0	28.2	28.7	28.2
1978	28.9	29.8	30.1	29.8	28.4	27.0	25.9	26.4	26.6	28.1	28.1	28.9	28.1
1979	28.8	30.7	30.4	29.6	27.4	26.8	25.9	25.8	27.4	28.3	27.9	28.5	28.1
1980	29.2	31.8	30.6	30.3	27.6	26.8	25.9	25.6	27.4	28.3	27.5	27.6	28.2

1981	29.0	29.5	29.8	30.2	28.2	26.9	25.6	26.3	26.6	28.1	27.9	29.1	28.1
1982	29.8	28.9	31.2	30.0	27.9	26.7	26.1	25.8	27.5	26.9	26.9	28.5	28.0
1983	28.3	29.5	31.4	29.6	28.2	26.9	25.9	25.9	27.2	27.6	27.3	28.7	28.0
1984	26.8	30.1	31.6	29.1	28.4	27.0	25.7	26.0	26.9	28.3	27.6	28.8	28.0
1985	30.4	28.2	29.6	26.9	27.3	26.2	25.2	25.9	26.8	28.0	28.5	28.4	27.6
1986	28.3	30.0	29.1	29.1	28.4	26.1	25.5	27.0	26.8	27.9	28.3	27.2	27.8
1987	28.5	31.1	30.6	30.1	27.3	27.2	27.2	28.3	28.5	28.2	28.4	29.2	28.7
1988	28.4	30.6	29.9	29.6	27.9	26.7	26.4	27.7	27.7	28.1	28.4	28.2	28.3
1989	25.0	27.3	29.3	31.6	30.0	26.1	25.4	25.6	26.0	26.5	26.0	24.9	27.0
1990	26.7	29.1	29.4	29.7	26.9	25.1	23.8	24.4	24.2	25.7	27.1	26.6	26.6
1991	27.8	28.1	30.3	30.0	28.3	26.9	25.5	25.6	26.8	26.4	26.9	25.9	27.4
1992	30.1	29.1	27.4	26.7	25.8	25.3	25.1	25.8	26.2	27.6	27.5	28.7	27.1
1993	30.1	30.3	29.4	28.6	27.0	26.2	26.4	26.6	28.0	28.2	28.7	27.3	28.1
1994	28.8	31.1	29.1	27.2	26.7	25.5	26.2	25.9	27.6	27.4	26.3	29.0	27.6
1995	29.5	29.8	30.2	28.2	26.9	25.6	26.3	26.6	28.1	27.9	29.1	26.9	27.9
1996	28.5	29.2	28.5	27.3	26.3	25.8	25.6	27.2	27.5	28.2	27.1	27.9	27.4
1997	29.0	29.2	29.9	28.2	27.2	24.7	26.3	26.9	27.8	27.7	28.7	26.7	27.7
1998	29.1	29.4	29.7	26.9	25.1	23.8	24.4	24.2	25.7	27.1	26.6	28.9	26.7
1999	28.5	30.2	29.6	27.5	26.8	25.9	25.4	26.2	26.7	27.0	27.3	28.9	27.5
2000	28.4	29.7	30.5	30.2	28.4	27.6	25.6	26.1	27.3	27.2	28.3	27.6	28.1
2001	27.0	29.8	30.9	29.7	28.7	26.3	25.8	26.3	26.7	27.1	27.4	28.2	27.8
2002	27.4	30.8	30.4	30.0	28.6	27.4	27.3	26.7	27.2	27.1	27.7	27.3	28.1
2003	29.3	30.4	30.6	30.1	28.1	26.5	25.8	25.9	26.6	28.2	27.3	27.2	28.0
2004	28.2	28.4	31.7	28.3	28.4	27.2	26.6	26.5	26.8	27.9	27.9	27.9	28.0
2005	28.1	32.3	31.6	31.9	27.8	27.1	25.7	26.4	27.0	27.4	28.4	29.3	28.6
2006	30.4	31.6	29.7	29.7	26.7	26.7	26.4	25.5	26.2	27.2	27.2	26.6	27.8
2007	27.6	30.2	31.0	30.2	28.6	26.4	25.7	25.7	26.1	27.5	27.7	28.2	27.9
2008	28.9	29.7	30.7	29.1	28.1	27.6	29.5	26.2	27.0	27.2	28.0	28.6	28.4
2009	29.2	30.7	30.3	28.2	28.1	27.9	27.4	27.2	27.2	28.0	28.5	29.2	28.5
Total	1700.2	1774.6	1803.5	1742.2	1660.1	1590.3	1548.3	1554.8	1600.2	1639.9	1654.7	1664.0	1661.1
Max	30.4	32.3	31.7	31.9	30.0	27.9	29.5	28.3	28.5	28.3	29.1	29.3	28.7
Mean	28.3	29.6	30.1	29.0	27.7	26.5	25.8	25.9	26.7	27.3	27.6	27.7	27.7
Stdev	1.1	1.1	0.9	1.1	0.8	0.7	0.8	0.7	0.8	0.7	0.7	1.0	0.5
CV	3.8	3.7	3.0	3.8	3.1	2.7	3.1	2.8	2.9	2.7	2.6	3.7	1.7

Appendix B. 3: Mean temperature at Malakal station C^0

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avearge
1950	25.0	26.5	30.0	30.3	28.0	26.9	25.0	25.5	26.4	26.9	26.8	26.0	26.9
1951	25.6	26.3	30.1	30.8	29.5	27.5	25.5	26.0	26.4	27.0	25.9	22.8	27.0
1952	26.5	28.0	30.0	30.5	29.5	27.7	26.5	25.8	26.4	27.2	27.6	27.5	27.8
1953	27.5	29.1	30.8	29.8	28.2	26.7	25.7	25.7	26.8	26.6	26.1	24.1	27.3
1954	25.1	28.9	30.9	30.3	28.9	26.1	25.0	25.3	26.0	26.9	27.4	24.7	27.1
1955	25.1	27.6	30.5	30.3	29.0	26.8	25.6	25.4	25.9	27.0	25.0	23.9	26.8
1956	23.6	28.3	30.4	31.1	29.5	26.0	25.6	25.3	26.1	26.5	27.5	26.0	27.2
1957	24.9	25.0	28.2	30.1	28.2	26.6	26.2	26.2	27.6	27.4	28.1	26.8	27.1
1958	26.5	26.1	31.1	31.5	29.2	26.2	25.4	25.7	26.8	27.0	27.8	26.8	27.5
1959	25.8	26.0	29.9	31.3	28.9	27.8	26.5	25.5	26.3	27.0	27.1	26.0	27.3
1960	25.5	28.7	28.2	29.6	28.9	27.3	26.3	26.3	26.2	26.9	26.6	28.0	27.4
1961	24.8	27.8	29.1	30.3	29.0	27.1	26.1	26.2	26.3	27.0	26.9	27.1	27.3
1962	24.1	26.9	30.0	30.9	29.0	26.9	25.8	26.0	26.3	27.0	27.1	26.2	27.2
1963	26.8	27.6	29.3	30.0	28.0	26.7	25.8	26.2	27.0	27.9	26.9	26.0	27.4
1964	25.2	26.7	30.3	30.1	28.3	26.4	24.2	24.7	25.2	25.7	26.2	24.2	26.4
1965	25.0	27.4	29.6	29.8	29.5	26.7	25.3	24.8	25.8	26.3	26.9	25.4	26.9
1966	26.0	26.6	29.2	28.9	26.1	25.6	25.1	25.4	25.8	26.1	26.0	25.2	26.3
1967	25.0	26.7	29.1	30.9	29.0	26.0	25.0	24.8	25.5	26.2	25.0	25.1	26.5
1968	24.8	25.4	29.3	30.1	28.7	25.7	25.1	24.8	25.5	26.2	26.9	25.4	26.5
1969	25.1	28.0	30.5	31.0	28.6	27.3	25.5	25.7	26.1	27.1	27.6	27.2	27.5
1970	25.0	27.7	30.6	31.0	28.6	27.1	25.1	25.8	25.7	26.5	27.1	25.6	27.1
1971	24.8	27.3	30.7	30.9	28.5	26.8	24.6	25.8	25.3	25.8	26.5	24.0	26.8
1972	25.5	26.1	39.7	30.1	27.7	25.9	25.7	25.5	26.0	26.7	26.1	25.5	27.5
1973	25.9	29.5	30.4	30.8	28.1	27.1	25.5	25.5	25.5	26.9	26.4	26.4	27.3
1974	25.3	28.2	29.7	30.8	26.8	25.7	24.9	25.3	25.3	26.8	26.7	24.9	26.7
1975	25.4	29.2	30.9	31.6	28.5	26.1	24.7	24.5	25.1	26.4	27.1	24.7	27.0
1976	25.5	27.0	30.5	30.5	28.3	26.5	25.2	25.1	25.7	26.7	26.4	27.3	27.1
1977	25.5	28.1	30.6	32.1	29.6	26.0	25.4	25.4	26.5	26.0	27.3	26.4	27.4
1978	26.0	27.5	30.2	30.8	28.5	26.6	25.2	25.5	25.6	27.0	26.6	27.2	27.2
1979	26.3	27.8	30.0	30.9	28.5	26.7	25.1	25.7	25.6	27.2	26.6	27.1	27.3
1980	26.4	27.9	29.9	30.9	28.6	26.7	25.1	25.8	25.5	27.2	26.7	27.0	27.3
1981	26.5	28.0	29.8	31.0	28.6	26.7	25.1	25.9	25.5	27.3	26.7	27.0	27.3
1982	26.5	28.7	30.6	32.1	28.5	27.3	26.6	26.1	27.0	27.6	26.8	25.0	27.7
1983	26.5	29.0	30.5	32.1	27.9	27.4	25.9	25.5	27.1	28.0	28.5	26.4	27.9
1984	26.0	26.3	29.5	31.0	28.9	27.5	25.8	25.5	26.7	27.0	28.5	27.2	27.5
1985	26.5	30.1	29.4	32.0	29.6	27.7	25.7	26.1	26.1	27.0	26.5	25.9	27.7
1986	26.2	26.5	30.5	32.1	29.0	26.9	26.0	25.4	26.3	26.8	27.0	25.5	27.4
1987	25.2	28.2	30.1	30.6	29.9	28.6	25.8	24.9	26.8	27.6	27.0	26.2	27.6
1988	25.0	29.7	29.0	29.4	30.6	26.2	25.6	25.4	26.6	27.9	26.6	26.4	27.4
1989	25.0	27.3	29.3	31.6	30.0	26.1	25.4	25.6	26.0	26.5	26.0	24.9	27.0
1990	25.8	25.9	29.9	30.5	28.9	26.1	25.0	25.3	26.9	26.9	26.8	23.8	26.8
1991	25.6	26.3	30.1	30.8	29.5	27.5	25.5	26.0	26.4	27.0	25.9	22.8	27.0
1992	28.3	30.4	31.1	29.5	26.0	25.6	25.3	26.1	26.5	27.5	26.0	25.5	27.3
1993	28.1	30.6	32.1	29.6	26.0	25.4	25.4	26.5	26.0	27.3	26.4	24.8	27.4
1994	27.3	30.7	30.9	28.5	26.8	24.6	25.8	25.3	25.8	26.5	24.0	26.5	26.9
1995	28.0	29.8	31.0	28.6	26.7	25.1	25.9	25.5	27.3	26.7	27.0	24.8	27.2

1996	25.4	29.3	30.1	28.7	25.7	25.1	24.8	25.5	26.2	26.9	25.4	25.1	26.5
1997	28.0	30.5	31.0	28.6	27.3	25.5	25.7	26.1	27.1	27.6	27.2	25.8	27.5
1998	25.9	29.9	30.5	28.9	26.1	25.0	25.3	26.9	26.9	26.8	23.8	25.8	26.8
1999	26.0	29.9	31.3	28.9	27.8	26.5	25.5	26.3	27.0	27.1	26.0	25.8	27.3
2000	29.4	28.9	30.0	31.5	29.3	27.8	26.3	25.7	27.0	27.5	28.1	26.7	28.2
2001	25.3	28.2	31.1	31.2	30.2	28.3	26.5	25.9	26.4	27.5	27.0	27.3	27.9
2002	25.3	29.2	31.0	32.5	31.9	27.8	27.2	25.0	27.4	27.8	29.9	28.8	28.6
2003	29.5	29.9	30.8	30.7	29.5	26.3	24.5	23.4	25.5	27.5	28.5	27.6	27.8
2004	28.0	28.9	32.1	32.2	31.3	28.3	27.7	26.5	27.7	29.0	29.4	28.3	29.1
2005	27.4	32.2	32.8	34.3	31.8	28.0	27.3	27.5	27.9	28.4	27.8	28.7	29.5
2006	29.3	30.9	31.9	32.5	29.9	28.2	27.8	27.3	27.7	28.3	27.4	26.2	28.9
2007	26.5	29.2	31.9	32.1	31.3	27.9	26.9	27.0	27.4	28.7	28.1	27.7	28.7
2008	28.2	29.0	32.3	29.9	29.9	27.8	29.8	26.6	29.4	28.3	28.5	28.7	29.0
2009	29.1	31.0	32.7	32.1	31.2	29.1	28.0	27.6	28.1	28.7	29.2	28.6	29.6
Total	1569	1693	1832.7	1840	1725	1605	1545	1543.3	1584.5	1626.5	1614.4	1564.0	1645.4
Max	29.5	32.2	39.7	34.3	31.9	29.1	29.8	27.6	29.4	29.0	29.9	28.8	29.6
Min	23.6	25.0	28.2	28.5	25.7	24.6	24.2	23.4	25.1	25.7	23.8	22.8	26.3
Mean	26.2	28.2	30.5	30.7	28.8	26.8	25.8	25.7	26.4	27.1	26.9	26.1	27.4
Stdev	1.3	1.6	1.5	1.1	1.4	1.0	0.9	0.7	0.8	0.7	1.1	1.4	0.7
CV	5.1	5.6	5.0	3.7	4.8	3.6	3.7	2.8	3.1	2.6	4.2	5.3	2.6

Appendix B. 4: Mean temperature at Wau station C^0

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	24.7	26.3	29.4	28.6	26.9	25.5	24.5	24.0	24.5	25.6	25.8	25.3	25.9
1951	24.8	25.8	29.7	29.0	27.7	26.5	25.1	25.0	25.2	25.7	26.1	23.4	26.2
1952	26.5	27.8	29.2	28.9	27.0	26.2	25.1	24.5	25.3	25.6	26.4	27.3	26.7
1953	26.9	28.1	29.6	29.1	27.1	25.7	24.3	24.6	25.5	25.5	25.7	23.4	26.3
1954	24.7	28.2	29.6	28.3	27.7	25.8	24.3	24.1	25.1	25.9	27.1	24.9	26.3
1955	25.5	27.0	29.0	28.1	26.8	25.8	24.8	24.0	24.7	26.7	26.1	24.3	26.1
1956	23.0	27.1	27.8	28.7	27.9	25.6	24.3	24.5	25.1	25.3	26.8	25.5	26.0
1957	24.7	24.9	27.9	28.3	27.7	26.2	25.5	24.9	25.8	26.1	27.1	26.6	26.3
1958	26.6	25.8	30.1	30.1	28.1	25.7	24.5	24.7	25.7	26.6	26.9	26.4	26.8
1959	25.9	25.7	29.1	29.2	27.7	26.3	25.5	24.7	25.2	25.7	26.7	26.1	26.5
1960	25.1	28.1	29.2	27.8	27.7	26.3	24.5	25.3	25.5	25.7	25.7	27.0	26.5
1961	24.2	27.2	29.1	28.3	27.4	26.1	24.7	25.0	25.4	25.8	26.3	26.3	26.3
1962	23.3	26.3	28.9	28.7	27.1	25.8	24.8	24.7	25.2	25.9	26.8	25.5	26.1
1963	26.1	26.5	27.9	27.8	27.2	25.9	25.0	24.8	26.0	26.7	26.1	25.2	26.3
1964	25.1	26.8	29.7	28.4	26.9	25.1	24.0	24.4	24.4	24.5	25.2	23.9	25.7
1965	24.6	26.2	28.7	28.7	28.7	26.3	25.5	24.8	25.2	25.1	26.3	25.6	26.3
1966	26.5	27.0	28.1	28.3	26.6	26.1	25.0	24.5	25.1	25.4	26.4	25.3	26.2
1967	26.2	26.5	28.2	28.2	26.8	25.7	24.9	24.8	25.2	25.5	26.5	25.5	26.1
1968	25.9	25.9	28.2	28.1	26.9	25.2	24.7	25.0	25.3	25.6	26.5	25.7	26.1
1969	27.6	28.6	28.7	28.9	28.1	26.3	24.8	24.8	25.4	25.8	26.6	26.3	26.8
1970	26.2	27.4	29.1	29.1	28.3	26.2	24.8	25.3	25.8	25.9	26.6	25.2	26.6
1971	24.8	26.1	29.4	29.2	28.5	26.1	24.8	25.7	26.2	25.9	26.6	24.0	26.4
1972	26.5	26.7	29.8	29.0	27.7	25.9	25.7	25.2	25.9	26.3	26.0	25.9	26.7
1973	26.3	29.5	30.1	28.4	27.1	26.6	25.4	24.3	25.1	26.5	26.4	26.3	26.8

1974	25.9	27.9	29.5	29.4	27.0	26.3	24.4	24.9	25.1	26.7	27.0	25.1	26.6
1975	25.7	29.3	30.1	30.3	28.3	26.1	25.5	24.6	24.8	25.9	27.3	25.3	26.9
1976	26.0	27.9	29.8	28.9	27.5	26.1	25.3	25.2	25.9	26.1	27.0	27.6	26.9
1977	26.0	28.1	29.5	30.5	28.7	26.4	25.3	25.3	25.7	25.9	26.5	26.3	27.0
1978	26.0	28.0	29.7	29.7	28.1	26.3	25.3	25.3	25.8	26.0	26.8	27.0	27.0
1979	26.3	28.0	29.6	29.9	28.1	26.7	25.5	25.6	26.0	26.5	26.9	27.5	27.2
1980	26.4	27.9	29.6	29.9	28.0	26.9	25.5	25.7	26.0	26.7	26.9	27.7	27.3
1981	26.5	27.9	29.6	30.0	28.0	27.1	25.6	25.9	26.1	26.9	27.0	28.0	27.4
1982	26.0	27.5	27.9	29.3	27.0	26.0	24.9	24.4	25.1	25.7	25.6	25.4	26.2
1983	26.2	27.7	27.9	29.6	27.0	25.9	24.8	24.4	25.1	25.6	25.7	25.6	26.3
1984	26.3	27.9	27.9	29.9	27.0	25.9	24.8	24.3	25.2	25.5	25.9	25.8	26.4
1985	25.7	27.0	27.9	28.6	26.9	26.0	24.9	24.5	24.9	25.9	25.2	25.0	26.0
1986	25.9	25.4	29.1	30.2	26.7	25.5	24.9	24.5	24.7	25.7	26.0	25.2	26.2
1987	26.1	27.9	28.9	29.3	28.1	25.3	24.5	23.7	24.5	25.4	25.2	25.2	26.2
1988	24.5	26.5	28.5	27.8	26.6	26.1	24.8	25.1	24.9	26.5	26.1	26.3	26.1
1989	24.9	27.9	28.8	29.0	28.6	25.7	25.2	25.1	25.3	25.1	25.8	24.8	26.4
1990	26.0	25.6	28.7	28.9	28.1	25.8	25.0	24.7	25.0	25.9	26.2	24.1	26.2
1991	24.8	25.8	29.7	29.0	27.7	26.5	25.1	25.0	25.2	25.7	26.1	23.4	26.2
1992	27.1	27.8	28.7	27.9	25.6	24.3	24.5	25.1	25.3	26.8	25.5	26.0	26.2
1993	28.1	29.5	30.5	28.7	26.4	25.3	25.3	25.7	25.9	26.5	26.3	24.8	26.9
1994	26.1	29.4	29.2	28.5	26.1	24.8	25.7	26.2	25.9	26.6	24.0	26.5	26.6
1995	27.9	29.6	30.0	28.0	27.1	25.6	25.9	26.1	26.9	27.0	28.0	25.9	27.3
1996	25.9	28.2	28.1	26.9	25.2	24.7	25.0	25.3	25.6	26.5	25.7	27.6	26.2
1997	28.6	28.7	28.9	28.1	26.3	24.8	24.8	25.4	25.8	26.6	26.3	26.0	26.7
1998	25.6	28.7	28.9	28.1	25.8	25.0	24.7	25.0	25.9	26.2	24.1	25.9	26.2
1999	25.7	29.1	29.2	27.7	26.3	25.5	24.7	25.2	25.7	26.7	26.1	25.9	26.5
2000	27.1	28.3	28.7	29.1	28.9	27.8	26.8	26.7	28.1	27.6	28.3	27.2	27.9
2001	26.1	28.2	30.8	30.6	29.6	29.9	26.9	26.3	27.3	28.1	27.7	27.4	28.2
2002	25.9	29.6	31.2	31.3	28.4	28.7	27.6	27.2	27.9	28.4	28.5	28.2	28.6
2003	28.5	30.1	30.6	29.5	30.1	27.7	26.6	26.3	27.6	28.5	28.6	28.7	28.5
2004	28.6	28.4	31.5	31.3	30.2	28.1	27.2	27.1	27.3	28.7	28.9	28.0	28.8
2005	27.4	31.9	32.2	32.3	29.5	28.0	26.6	27.0	27.3	28.2	28.4	28.8	28.9
2006	28.9	30.7	31.1	32.4	28.4	27.7	27.0	26.7	27.3	28.1	27.2	25.5	28.4
2007	25.8	28.4	30.6	31.3	29.5	27.3	27.1	26.7	27.1	28.0	28.0	27.3	28.1
2008	25.8	28.4	30.6	31.3	29.5	27.3	27.1	26.7	27.1	28.0	28.0	27.3	28.1
2009	28.7	30.6	31.3	30.6	30.1	28.8	27.8	27.3	27.8	28.6	28.9	28.5	29.0
Total	1564	1664	1760.8	1750	1659.8	1574	1518.7	1513.4	1544.5	1581.6	1593.9	1561.3	1607.3
Max	28.9	31.9	32.2	32.4	30.2	29.9	27.8	27.3	28.1	28.7	28.9	28.8	29.0
Min	23.0	24.9	27.8	26.9	25.2	24.3	24.0	23.7	24.4	24.5	24.0	23.4	25.7
Mean	26.1	27.7	29.3	29.2	27.7	26.2	25.3	25.2	25.7	26.4	26.6	26.0	26.8
Stdev	1.2	1.4	1.0	1.1	1.1	1.0	0.9	0.9	0.9	1.0	1.0	1.3	0.8
CV	4.7	5.1	3.4	3.9	4.0	3.9	3.5	3.4	3.5	3.7	3.9	5.0	3.1

Appendix C: Study results

Appendix C. 1: Potential Evaporation by Thronthwaite Method mm

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	184.9	193.4	217.4	164.0	128.0	103.8	73.3	87.0	103.5	97.9	139.8	175.6	1668.6
1951	186.3	184.9	215.5	195.8	143.3	104.3	86.8	89.4	121.2	116.5	130.3	139.9	1714.3
1952	186.4	204.9	182.1	145.5	112.1	102.5	94.6	90.0	114.6	115.9	139.3	182.8	1670.5
1953	198.6	210.0	222.3	167.0	128.5	99.1	86.7	85.3	118.9	152.8	132.0	156.5	1757.6
1954	171.0	239.8	233.1	124.4	106.3	92.6	82.6	79.3	96.3	125.1	137.4	155.1	1643.0
1955	208.8	195.7	203.1	170.5	111.4	98.7	82.4	80.5	90.7	121.2	140.8	174.0	1677.9
1956	142.3	220.0	167.6	123.8	95.3	90.7	88.1	81.9	96.9	115.8	135.4	161.0	1518.8
1957	158.3	147.3	179.5	137.4	129.6	90.2	87.7	86.1	110.5	154.0	147.3	173.5	1601.5
1958	215.7	164.7	235.9	187.9	140.4	95.3	94.2	77.3	94.4	108.0	162.9	188.1	1764.8
1959	192.2	153.7	210.9	149.6	120.9	109.6	99.7	90.9	98.6	118.7	129.1	136.4	1610.1
1960	184.5	227.8	219.1	140.6	122.0	98.0	85.8	98.7	115.7	116.3	154.2	199.4	1762.0
1961	226.1	167.8	194.6	170.0	143.2	105.0	85.4	84.0	108.5	107.5	103.3	129.3	1624.7
1962	119.7	171.8	162.2	135.8	115.4	99.4	96.6	95.0	111.5	119.0	132.1	148.2	1506.7
1963	179.6	169.2	181.8	123.4	109.7	97.2	89.8	94.1	131.2	160.2	121.6	170.2	1628.1
1964	181.1	197.2	218.0	131.6	123.2	94.2	85.5	83.4	101.1	114.3	135.5	146.3	1611.4
1965	180.8	193.4	233.4	161.5	114.5	99.7	79.2	98.0	115.4	115.3	144.6	181.3	1717.0
1966	218.4	177.6	161.9	138.4	116.0	115.3	90.0	92.0	101.0	128.7	136.7	169.8	1645.7
1967	180.4	189.9	200.4	193.7	141.3	93.0	76.3	80.9	93.6	123.4	109.4	141.3	1623.7
1968	145.3	168.0	181.3	144.5	112.8	92.6	105.1	82.2	112.1	117.8	156.0	155.8	1573.6
1969	166.0	165.4	184.3	156.8	133.9	115.8	80.8	103.9	109.1	139.7	142.9	167.5	1666.0
1970	198.4	240.2	232.7	177.1	145.4	95.5	90.6	91.6	116.6	124.9	156.1	149.9	1818.9
1971	173.0	190.7	239.9	173.2	122.0	101.0	86.6	98.0	105.4	139.4	140.3	148.7	1718.3
1972	210.2	215.6	239.4	179.3	164.7	101.4	111.2	100.3	144.1	139.2	131.6	172.1	1909.1
1973	227.6	267.6	275.8	163.2	123.9	100.5	93.2	90.0	116.7	163.9	148.1	198.8	1969.3
1974	186.4	256.5	227.3	130.0	110.3	103.6	89.3	89.9	100.9	142.2	147.3	154.0	1737.7
1975	197.2	243.2	223.3	184.1	126.7	89.9	87.4	85.0	104.0	127.4	164.8	191.7	1824.7
1976	194.5	207.0	195.9	153.4	100.7	101.1	92.9	89.2	118.7	153.6	149.1	208.6	1764.8
1977	196.8	218.8	234.5	173.8	149.7	95.3	86.4	94.7	101.5	157.4	155.4	194.8	1859.1
1978	193.3	196.9	207.0	175.4	132.1	100.4	103.5	90.0	100.3	127.0	151.9	202.8	1780.6
1979	188.5	210.5	218.4	150.9	118.0	107.0	97.4	93.8	116.3	149.2	146.8	161.3	1758.1
1980	226.9	292.5	252.9	203.3	128.0	110.3	84.4	90.8	136.9	144.7	150.1	170.7	1991.5
1981	222.2	212.1	204.1	204.5	140.8	102.5	85.5	97.4	115.3	149.3	150.1	225.5	1909.4
1982	178.6	230.1	178.4	159.8	120.2	85.2	83.7	87.5	106.1	117.0	106.2	126.2	1579.0
1983	177.4	195.5	173.8	129.2	104.3	84.7	72.5	71.4	95.7	137.5	142.9	171.1	1555.9
1984	166.7	156.7	168.0	124.2	102.8	83.5	76.0	70.6	93.8	126.4	150.0	186.5	1505.1
1985	199.8	179.5	152.1	146.2	94.5	96.9	70.1	77.6	84.6	110.7	167.5	183.0	1562.6
1986	179.2	160.6	206.4	163.7	82.9	78.8	89.0	73.4	88.1	106.9	109.9	128.7	1467.8
1987	179.7	188.4	198.6	127.2	102.3	68.6	63.9	63.8	78.0	103.9	103.8	146.2	1424.4
1988	143.1	151.0	153.1	163.3	90.9	80.6	85.0	70.7	83.9	104.7	143.7	146.9	1416.8
1989	108.6	129.7	185.0	191.2	170.6	99.8	93.9	95.6	97.0	116.5	112.3	95.8	1496.0
1990	159.1	194.7	207.2	180.6	118.1	89.3	65.1	80.9	87.7	100.8	144.7	151.0	1579.2
1991	186.3	172.5	215.5	195.8	143.3	104.3	86.8	89.4	121.2	116.5	130.3	139.9	1702.0
1992	234.2	200.0	137.4	117.3	104.6	84.5	86.9	98.2	115.4	134.8	131.7	182.5	1627.4
1993	251.3	226.9	196.7	146.7	106.3	89.0	99.2	102.4	142.4	164.3	160.3	168.0	1853.5
1994	197.4	261.9	181.3	105.7	104.1	82.2	98.9	90.5	129.9	138.3	115.7	201.1	1707.1
1995	238.7	221.0	217.8	152.2	102.0	81.1	91.3	102.9	139.6	141.6	194.0	171.5	1853.8

1996	200.4	190.3	155.0	121.4	88.7	89.2	90.5	111.0	123.4	153.9	125.3	169.9	1619.1
1997	205.4	190.9	219.4	145.4	121.4	66.5	89.3	104.1	123.8	151.2	167.7	144.1	1729.2
1998	197.9	182.0	191.9	115.5	82.4	64.1	86.4	67.6	90.9	111.9	124.7	200.7	1516.0
1999	181.5	194.8	194.3	110.7	108.8	95.3	92.1	103.2	106.5	124.3	135.0	172.2	1618.6
2000	201.1	216.3	246.5	198.3	145.2	125.8	80.9	99.6	135.2	121.1	170.4	169.8	1910.2
2001	164.2	220.5	235.0	189.4	151.9	93.2	89.6	97.7	117.3	127.5	138.5	195.7	1820.5
2002	159.3	258.3	211.1	188.3	156.2	113.2	118.2	108.7	130.4	123.0	134.1	147.4	1848.2
2003	221.9	228.1	233.3	181.4	125.4	93.8	90.1	90.9	114.4	164.4	128.3	165.6	1837.6
2004	180.7	180.0	260.4	123.4	133.1	105.6	103.4	98.4	114.0	148.5	145.9	170.9	1764.3
2005	192.6	321.5	269.1	264.7	115.2	101.6	80.1	96.4	115.6	128.2	172.7	247.9	2105.5
2006	263.2	264.9	184.5	172.1	93.4	101.5	100.5	83.3	99.3	131.0	125.3	138.6	1757.6
2007	166.7	220.6	255.0	192.9	148.6	87.3	79.8	85.3	93.7	145.1	144.3	179.4	1798.8
2008	193.3	194.5	226.8	158.3	124.9	110.9	182.6	86.3	105.5	109.6	150.3	192.2	1835.3
2009	201.9	214.1	218.5	120.9	131.0	127.8	122.3	116.8	111.6	142.9	160.6	179.5	1847.9
Total	11371	12239	12428	9516.4	7282.7	5789.6	5427.1	5395.0	6566.4	7789.0	8458.5	10103	102367
Max	263.2	321.5	275.8	264.7	170.6	127.8	182.6	116.8	144.1	164.4	194.0	247.9	2105.5
Min	108.6	129.7	137.4	105.7	82.4	64.1	63.9	63.8	78.0	97.9	103.3	95.8	1416.8
Mean	189.5	204.0	207.1	158.6	121.4	96.5	90.5	89.9	109.4	129.8	141.0	168.4	1706.1
Stdev	28.5	36.4	30.6	30.1	19.9	12.3	16.2	10.7	15.1	17.8	18.0	26.0	145.2
CV	15.0	17.9	14.8	19.0	16.4	12.7	17.9	12.0	13.8	13.7	12.8	15.5	8.5

Appendix C. 2: Potential Evaporation by Hamon Method

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1950	118.1	115.7	134.9	125.4	119.7	107.3	100.9	102.1	100.3	104.0	108.3	117.1	1353.8
1951	118.1	109.4	140.0	134.3	125.8	112.1	106.0	105.9	109.4	109.3	108.3	104.8	1383.4
1952	122.6	115.7	132.4	120.1	111.1	110.0	107.3	104.0	105.4	110.7	115.2	124.6	1379.1
1953	123.4	121.6	140.0	130.2	125.0	111.4	106.0	104.6	109.4	118.5	111.7	110.8	1412.6
1954	118.1	127.0	146.2	120.8	114.6	107.3	102.7	102.1	101.6	111.4	111.7	113.6	1377.1
1955	124.1	115.7	135.8	126.2	119.0	110.7	106.0	101.4	99.1	112.1	108.3	111.5	1369.9
1956	106.3	123.9	130.0	114.3	113.9	104.7	104.7	102.7	102.9	108.0	113.1	115.7	1340.2
1957	113.8	104.8	125.2	117.2	120.5	109.3	110.0	105.9	110.8	119.2	114.5	118.6	1369.8
1958	132.1	112.9	146.2	136.8	129.8	110.0	104.7	104.6	105.4	113.5	119.6	122.3	1437.9
1959	126.5	112.2	139.2	131.0	119.7	111.4	108.6	104.6	105.4	111.4	108.9	114.3	1393.2
1960	118.1	122.3	134.9	117.2	117.5	105.3	108.0	107.9	105.4	112.1	113.1	123.9	1385.7
1961	128.8	108.1	134.1	126.2	125.8	112.1	104.7	102.7	104.1	105.3	98.0	100.9	1350.8
1962	101.2	108.7	126.0	116.4	111.8	108.0	107.3	105.3	103.5	111.4	112.4	113.6	1325.6
1963	118.1	110.8	128.4	114.3	116.8	110.0	106.6	107.9	113.6	120.7	107.6	114.3	1369.1
1964	121.1	114.3	141.8	123.9	122.0	108.0	104.0	104.0	103.5	107.3	111.0	110.8	1371.7
1965	116.7	115.0	144.4	123.1	120.5	111.4	104.7	109.9	109.4	110.0	109.6	113.6	1388.3
1966	128.0	113.6	127.6	120.1	124.3	116.3	106.6	108.6	105.4	113.5	113.8	118.6	1396.4
1967	120.3	117.1	131.6	136.8	125.0	110.7	104.0	103.3	103.5	108.6	101.1	108.7	1370.7
1968	111.7	112.2	130.8	122.4	118.3	108.0	108.0	105.9	112.2	117.0	117.4	112.9	1376.8
1969	118.9	115.7	130.8	133.4	125.0	114.2	100.9	110.6	110.1	119.2	113.8	124.6	1417.2
1970	121.8	127.0	138.3	129.4	126.6	104.7	110.7	105.3	106.1	115.6	113.8	110.1	1409.4
1971	114.5	114.3	147.2	127.0	117.5	110.7	106.0	109.9	103.5	117.8	111.7	107.4	1387.5
1972	128.8	117.9	148.1	131.0	130.6	110.7	115.6	109.9	116.4	120.0	113.1	121.6	1463.7
1973	130.4	134.3	152.7	128.6	123.5	112.8	110.0	107.9	109.4	122.2	117.4	122.3	1471.5

1974	122.6	130.2	143.5	123.1	116.8	112.8	106.6	107.9	104.1	117.8	115.2	113.6	1414.2
1975	121.1	127.0	140.9	130.2	125.8	107.3	109.3	104.6	105.4	114.9	115.9	116.4	1418.8
1976	121.8	119.3	138.3	125.4	117.5	110.7	108.6	107.9	112.9	122.2	118.1	129.4	1432.1
1977	124.9	123.9	140.0	129.4	128.2	112.8	110.7	111.3	108.1	120.7	117.4	124.6	1452.0
1978	126.1	121.6	137.9	132.6	126.6	112.4	108.6	111.0	108.1	121.1	116.3	126.2	1448.5
1979	125.3	128.2	140.5	131.0	119.0	111.0	108.6	106.9	113.2	122.6	115.2	122.7	1444.2
1980	128.8	137.6	142.7	136.8	120.5	111.4	108.6	105.9	113.6	123.0	112.4	116.4	1457.7
1981	127.2	119.3	135.8	136.0	125.0	112.1	106.6	110.6	108.1	121.5	115.2	127.8	1445.2
1982	120.3	124.6	131.6	125.4	113.9	101.5	101.5	102.1	101.6	110.7	102.4	106.1	1341.7
1983	117.4	118.6	126.0	116.4	113.9	103.4	97.2	95.9	99.1	112.7	115.2	114.3	1330.1
1984	116.7	104.8	126.0	120.8	112.5	102.1	98.4	96.5	99.7	111.4	115.9	123.1	1327.9
1985	121.8	111.5	119.2	117.9	110.5	109.3	98.4	99.0	95.5	107.3	116.6	113.6	1320.6
1986	117.4	108.7	144.4	130.2	107.1	98.4	104.7	97.7	98.5	104.0	103.0	104.8	1318.9
1987	120.3	117.9	132.4	112.9	107.8	96.0	94.8	91.9	94.3	99.6	97.4	109.4	1274.7
1988	110.3	108.7	121.4	130.2	107.1	100.9	97.8	98.3	98.5	110.7	113.1	109.4	1306.4
1989	99.3	104.1	131.6	148.3	139.8	106.6	105.3	105.9	104.1	110.0	102.4	98.5	1355.9
1990	110.3	116.4	132.4	131.8	115.4	100.2	95.4	98.3	93.1	104.7	109.6	109.4	1317.0
1991	118.1	109.4	140.0	134.3	125.8	112.1	106.0	105.9	109.4	109.3	108.3	104.8	1383.4
1992	136.2	116.4	117.0	109.4	107.8	101.5	103.4	107.3	105.4	117.8	112.4	124.6	1359.2
1993	136.2	125.4	132.4	123.1	116.1	107.3	112.1	112.7	117.9	122.2	121.0	114.3	1440.7
1994	125.7	131.8	130.0	112.9	113.9	102.7	110.7	107.9	115.0	116.3	104.3	127.0	1398.2
1995	131.2	121.6	139.2	120.1	115.4	103.4	111.4	112.7	118.6	120.0	124.1	111.5	1429.2
1996	123.4	117.1	125.2	113.6	111.1	104.7	106.6	117.0	114.3	122.2	109.6	118.6	1383.4
1997	127.2	117.1	136.6	120.1	117.5	97.8	111.4	114.8	116.4	118.5	121.0	110.1	1408.5
1998	128.0	118.6	134.9	110.8	103.2	92.5	99.0	97.1	102.2	114.2	106.3	126.2	1333.0
1999	123.4	124.6	134.1	115.0	114.6	105.3	105.3	109.9	108.8	113.5	111.0	126.2	1391.7
2000	122.6	120.8	141.3	135.5	126.6	117.0	106.6	109.3	112.9	114.5	118.1	116.1	1441.3
2001	112.4	121.6	144.9	131.8	129.0	107.6	108.0	110.3	108.4	113.8	111.3	120.5	1419.6
2002	115.2	129.3	140.5	133.9	127.8	115.2	118.1	113.1	111.8	114.2	113.8	114.3	1447.2
2003	129.2	125.8	142.7	134.7	123.9	109.3	108.0	107.6	108.1	122.2	110.6	113.6	1435.7
2004	121.1	111.5	152.3	120.5	126.2	113.8	113.1	112.0	109.4	120.0	114.8	118.6	1433.3
2005	120.3	142.0	151.3	151.1	121.6	113.5	107.3	111.0	110.8	115.9	118.4	129.4	1492.6
2006	138.8	135.5	134.9	131.8	113.9	110.7	111.7	105.0	105.1	114.5	110.0	109.4	1421.3
2007	116.7	124.6	145.8	135.5	127.8	108.6	107.0	106.6	104.5	116.7	113.8	120.5	1428.1
2008	126.1	120.8	143.1	127.0	123.9	117.0	135.8	109.6	110.5	114.5	115.9	123.5	1467.7
2009	128.8	128.5	140.0	119.7	124.3	119.2	118.9	116.6	111.8	120.7	119.6	128.2	1476.3
Total	7293.7	7155.0	8197.4	7565.3	7182.1	6505.2	6415.5	6375.1	6415.0	6874.7	6739.0	6979.7	83697.7
Max	138.8	142.0	152.7	151.1	139.8	119.2	135.8	117.0	118.6	123.0	124.1	129.4	1492.6
Min	99.3	104.1	117.0	109.4	103.2	92.5	94.8	91.9	93.1	99.6	97.4	98.5	1274.7
Mean	121.6	119.3	136.6	126.1	119.7	108.4	106.9	106.3	106.9	114.6	112.3	116.3	1395.0
Stdev	7.7	8.4	8.0	8.8	7.1	5.4	6.2	5.1	5.8	5.6	5.5	7.5	48.7
CV	6.3	7.0	5.8	6.9	6.0	5.0	5.8	4.8	5.4	4.9	4.9	6.4	3.5

Appendix C. 3: Flooding area of Sudd Swamp result from Thronthwiate Evaporation Million m2

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	0.0	0.0	13175.0	13598.8	14066.1	15838.7	17482.2	19579.7	20137.8	20916.8	19175.7	17023.9	14249.6
1951	15346.6	13481.1	11299.0	10083.8	9631.6	9690.0	10866.8	12115.4	12399.9	12797.4	12099.5	10914.5	11727.1
1952	9438.8	8421.3	7779.5	7540.0	8096.3	8455.7	9315.9	11150.9	12234.0	13128.0	12891.5	11766.4	10018.2
1953	10926.6	9424.9	8060.6	7347.2	7586.8	8658.6	9927.8	11338.5	11444.1	11858.5	11185.9	9978.5	9811.5
1954	8678.0	7321.8	6329.0	6183.1	6422.4	6859.3	8321.3	9597.6	10853.1	11094.0	10600.6	10187.9	8537.3
1955	9012.4	7753.0	7040.5	7082.3	6989.9	7243.1	7845.8	8932.7	10437.7	10696.6	10182.8	9844.2	8588.4
1956	9925.5	8755.3	7695.1	7688.5	7624.5	8222.9	9251.3	11737.7	12617.7	13267.6	12139.0	11507.1	10036.0
1957	11039.2	10028.8	9365.5	8727.1	9083.6	9997.2	11188.0	12919.7	13121.6	12952.1	12230.6	10708.5	10946.8
1958	8979.3	7936.3	6682.4	6205.0	6075.8	7105.6	8000.4	8780.7	9821.1	10527.5	10017.6	9057.7	8265.8
1959	8008.4	7087.8	6115.0	5745.0	5987.1	6117.5	6836.8	7922.0	8848.7	9439.8	9192.6	8531.6	7486.0
1960	7806.5	6730.2	5919.6	6196.6	6187.4	6518.1	7362.1	8287.0	8989.7	9632.7	9173.0	8492.3	7607.9
1961	7878.0	7436.6	6648.3	6136.4	6095.4	6399.6	7897.8	9050.8	10238.1	11721.8	12355.5	12587.7	8703.8
1962	13043.5	13333.4	13393.6	13453.2	14027.3	15284.8	17151.2	19680.1	22073.4	23929.0	23097.7	21894.2	17530.1
1963	20654.1	19525.8	18645.0	19495.3	20417.2	23020.3	25338.9	29378.5	31754.1	32061.3	31783.0	29217.0	25107.5
1964	26240.6	24020.8	21730.0	21466.7	22598.4	23152.8	26922.1	31307.0	34659.1	37096.8	35612.7	34239.6	28253.9
1965	32638.8	29846.0	25925.9	26097.1	26026.7	26682.8	28602.9	31748.9	33812.3	34830.0	32845.0	29725.2	29898.5
1966	26192.1	24193.9	23542.7	23286.9	23410.8	23945.2	26189.0	28960.8	31201.5	33291.9	30977.5	27823.7	26918.0
1967	25098.5	22987.6	20978.2	19056.2	18930.2	20034.4	22744.8	25612.1	28031.2	29346.6	29479.8	27591.5	24157.6
1968	25935.5	24090.6	21989.3	20870.4	20302.6	21825.0	23654.6	27157.9	28095.4	29025.8	27649.9	25821.2	24701.5
1969	23684.4	21888.8	21232.4	20234.0	20332.7	21252.4	23373.1	26165.5	27732.2	28218.4	27140.5	24466.0	23810.0
1970	22102.7	19340.4	17995.1	17505.9	17066.2	18050.2	20071.0	22901.0	24819.0	26174.4	25465.5	25437.1	21410.7
1971	24729.2	22999.4	19832.2	18913.0	20198.0	20369.5	22784.1	26033.4	27613.0	28036.7	26373.6	25167.1	23587.4
1972	22439.3	20006.8	16973.1	16617.2	16585.8	17113.0	18532.1	20709.1	21571.7	21853.9	20678.3	18377.4	19288.1
1973	16254.8	14401.6	12843.6	12985.2	13407.7	13961.6	15516.9	18041.0	19778.3	20472.7	19291.5	17588.5	16211.9
1974	16110.1	14196.5	12815.2	12988.4	14078.0	14804.8	16589.1	18901.1	20984.0	21202.8	20189.9	19119.1	16831.6
1975	17653.3	15483.6	13800.6	13302.0	13956.2	15335.5	16661.6	20839.4	22661.3	23220.5	22162.0	21048.5	18010.4
1976	19664.4	17640.0	16063.8	16041.9	16962.8	17604.5	19285.4	21423.4	21881.7	21927.4	20854.3	18581.7	18994.3
1977	16730.3	14845.7	13504.7	13205.7	13347.4	14515.5	15909.4	18371.1	19443.1	19955.5	19069.4	17495.2	16366.1

1978	16122.3	14870.3	14008.5	13715.6	12578.1	13141.4	14718.0	17423.7	18649.5	19706.4	19299.0	17812.4	16003.8
1979	16946.3	15465.4	14272.2	14539.3	15796.9	18022.6	20653.3	22814.3	24319.4	24653.2	23644.9	21129.2	19354.8
1980	18743.5	15909.2	14485.6	13753.5	15142.9	16542.5	19007.4	21629.9	22785.7	23563.5	22722.3	20607.7	18741.1
1981	18217.8	16529.0	15264.5	14518.5	14832.6	16655.0	19096.3	22207.5	24053.8	23543.2	22145.9	19123.3	18848.9
1982	17439.9	15520.9	14220.3	13644.3	13987.0	15341.5	16286.1	17467.6	18479.6	19384.1	18781.6	17809.8	16530.2
1983	16576.5	15381.6	14617.3	14197.5	14151.8	15336.2	16692.2	18726.4	20027.0	20918.8	19968.7	18330.3	17077.0
1984	16767.6	15824.0	14964.4	15298.3	15881.4	16593.9	19110.3	20419.2	21698.5	21658.4	20806.3	18722.8	18145.4
1985	17198.3	15774.6	15564.5	15767.7	16574.9	17183.4	18253.9	19367.5	20806.1	21486.1	20425.3	18677.6	18090.0
1986	16966.2	16235.1	14551.1	14165.5	14285.5	15607.9	17310.7	18677.4	19701.5	20761.7	20237.0	19036.6	17294.7
1987	16943.5	15046.8	13345.4	13249.6	14011.9	14578.0	14996.7	15760.6	16723.7	17327.9	17650.9	16325.5	15496.7
1988	15163.9	14150.9	13361.6	12739.2	13386.4	14268.7	16512.2	18526.3	20854.8	21449.9	20622.0	19693.6	16727.4
1989	19134.1	18138.9	18042.2	17040.8	16463.9	17631.8	19529.7	21404.2	22885.8	23642.3	24370.5	23710.7	20166.3
1990	22336.7	20595.4	19120.0	17836.4	17616.6	17550.1	19325.8	21707.7	23235.3	24365.8	23629.4	22239.5	20796.6
1991	20432.9	19226.6	16796.2	15877.4	15631.1	16002.7	18024.2	19919.7	20573.8	21932.1	22001.4	21267.8	18973.8
1992	18381.1	17184.1	17109.0	17811.6	18506.9	19016.7	20786.3	23657.8	24776.4	25717.8	25003.5	22579.8	20877.6
1993	19497.8	17551.0	16944.2	17950.8	18297.6	19202.4	20633.6	21156.3	21983.0	22099.5	21254.0	20209.6	19731.7
1994	18576.5	16584.6	16393.9	16831.0	17598.3	18883.5	20505.3	21830.4	22681.5	23379.0	23228.5	20595.0	19757.3
1995	18111.1	16418.1	15577.6	15385.3	16054.6	16294.3	17735.6	18535.0	19509.6	20454.7	19162.9	18210.7	17620.8
1996	16611.3	15291.8	15202.5	16041.4	16816.4	17716.5	19186.9	19411.5	20866.3	22002.4	21633.0	20027.9	18400.7
1997	18192.0	16856.2	16001.7	17472.7	17681.9	18594.0	19810.6	21023.1	21622.3	24001.2	23788.2	23080.8	19843.7
1998	20936.0	19221.6	17991.8	18893.0	19286.4	21157.2	23675.2	25189.1	25765.4	27845.3	27725.5	24353.5	22670.0
1999	21819.6	19307.0	18147.0	19811.6	20318.0	22298.5	23915.0	26280.7	28328.8	30479.3	29120.7	25529.7	23779.7
2000	23173.5	20845.0	18760.4	18141.3	17961.9	18962.6	21181.7	23112.9	24370.0	24953.5	24269.2	23614.3	21612.2
2001	22235.5	19938.3	18066.5	16673.4	15781.0	17049.0	18590.3	20599.8	22517.7	23604.4	23732.6	23003.1	20149.3
2002	21255.2	18235.6	16461.7	16660.7	15849.0	16503.6	17462.9	19169.0	20483.0	21975.2	20999.9	20758.1	18817.8
2003	18535.8	16573.7	14081.0	12673.3	12446.2	13875.4	16129.1	17231.4	18464.6	18612.8	19657.5	18357.3	16386.5
2004	16792.5	15648.1	13686.6	13466.0	13391.8	14269.0	15978.2	17467.6	18808.8	19760.6	20452.6	19647.2	16614.1
2005	18236.0	14979.3	13050.3	11878.8	12427.4	13430.8	14719.5	17141.3	18197.7	19379.2	18663.8	17447.7	15796.0
2006	15492.3	13763.8	12907.1	12784.7	13391.2	14603.2	15896.1	17354.8	18415.3	19600.7	19948.5	19755.9	16159.5
2007	18479.9	16367.8	14447.1	14494.3	14713.8	15892.3	18204.4	20087.1	21899.7	22360.3	21854.9	19706.2	18209.0
2008	17783.4	15870.9	14062.7	14034.6	14146.1	14220.4	15034.8	16605.9	18883.7	20391.5	20229.0	18374.5	16636.5

2009	17463.1	15990.3	15011.0	16674.7	16421.0	16590.5	17967.7	20262.9	22337.9	22972.7	22397.3	20200.1	18690.8
Total	1046773.2	948473.4	883890.5	872075.7	886925.4	941074.7	1040552.7	1160811.6	1241961.0	1292660.0	1253341.6	1164131.7	1061056.0
Max	32638.8	29846.0	25925.9	26097.1	26026.7	26682.8	28602.9	31748.9	34659.1	37096.8	35612.7	34239.6	29898.5
Min	7806.5	6730.2	5919.6	5745.0	5987.1	6117.5	6836.8	7922.0	8848.7	9439.8	9173.0	8492.3	7486.0
Mean	17446.2	15807.9	14731.5	14534.6	14782.1	15684.6	17342.5	19346.9	20699.4	21544.3	20889.0	19402.2	17684.3
Stdev	5618.1	5198.6	4453.9	4490.7	4540.0	4713.7	5113.8	5638.5	5979.1	6198.7	5980.5	5562.1	5132.6
CV	32.2	32.9	30.2	30.9	30.7	30.1	29.5	29.1	28.9	28.8	28.6	28.7	29.0

Appendix C. 4: Flooding area of Sudd Swamp result from Hamon Evaporation Million m2

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	0.0	0.0	13175.0	14167.6	15132.7	17238.4	18704.1	20723.8	21362.2	22372.2	21481.9	20531.2	15407.4
1951	19782.4	18701.1	17240.5	16371.6	16335.0	16607.7	17939.6	19375.4	19754.9	20413.9	19966.8	18685.7	18431.2
1952	17352.4	16412.5	15669.2	15279.0	16090.2	16611.8	17506.6	19703.1	21121.2	22387.7	22307.3	21456.8	18491.5
1953	20750.3	19373.3	17842.5	16941.1	17483.6	19200.0	20784.9	22644.6	22690.3	23466.0	22664.8	21070.1	20409.3
1954	19438.6	17958.8	16672.5	16269.3	16749.0	17488.6	19458.1	21020.1	22815.2	23157.9	22289.5	21545.4	19571.9
1955	20192.0	18594.7	17557.2	17679.2	17544.3	17848.7	18409.3	19784.5	22019.1	22348.9	21578.7	20906.1	19538.6
1956	20577.2	19434.0	18183.1	17896.7	17739.5	18643.6	19837.0	23206.2	24423.9	25502.1	24177.0	23360.3	21081.7
1957	22593.0	21222.5	20826.9	19886.9	20662.8	22226.3	23723.5	25959.9	25850.9	25754.2	25144.8	23468.2	23110.0
1958	21554.5	20059.4	18342.3	17613.2	17388.9	19119.4	20260.6	20937.9	22428.2	23163.3	22283.0	21072.5	20351.9
1959	19668.9	18348.9	16930.3	16337.7	16726.9	16696.2	17518.5	18798.7	20128.1	21036.1	20487.2	19424.6	18508.5
1960	18351.3	17055.1	15860.0	16235.0	16038.7	16280.7	17242.4	18246.9	19188.8	20093.5	19329.7	18545.6	17705.6
1961	17827.7	17050.7	15994.3	15117.0	15024.5	15455.1	17529.7	18940.6	20631.6	22767.8	23215.5	23138.9	18557.8
1962	23337.8	23624.2	23807.9	23783.2	24693.9	26407.3	28298.7	31003.4	33961.9	36387.5	35976.1	35200.0	28873.5
1963	34428.9	33632.7	33127.3	34253.0	35866.9	39731.3	41844.7	46336.8	49491.8	50236.9	50567.9	48472.7	41499.3
1964	45993.2	44220.0	42314.7	42041.4	44565.3	45242.7	49944.2	55384.0	59829.4	63025.1	61542.2	60169.5	51189.3
1965	58613.9	56043.5	52403.4	52889.0	53076.6	53736.3	55166.9	59165.8	62288.0	63659.3	61339.0	57815.2	57183.1
1966	54342.1	51848.7	51355.0	50755.0	51640.7	52546.6	54836.7	58290.7	61602.7	65260.6	62565.5	58790.2	56152.9
1967	55279.6	52617.9	49563.0	46354.2	46642.0	48455.0	52308.5	56163.8	59938.2	61809.4	61341.1	58292.9	54063.8
1968	55524.7	53144.5	49953.4	47943.7	47170.3	49909.9	51887.9	56796.7	57922.1	59342.5	57885.6	55434.0	53576.3
1969	52499.3	50346.3	49824.6	48353.6	48889.3	50080.0	52112.7	55561.0	57711.4	58404.0	56722.8	53767.7	52856.1

1970	50628.5	47479.2	45899.2	44661.3	44024.2	45042.6	47436.4	51092.6	53620.3	55619.4	53965.3	52910.4	49365.0
1971	51394.8	49187.9	45715.7	43821.2	46498.5	45957.2	48787.7	53304.5	55243.9	56007.4	53658.4	51475.8	50087.8
1972	48679.9	45883.4	42362.8	42160.3	42567.8	43040.9	44753.2	47803.0	49129.1	49554.5	47686.9	44497.3	45676.6
1973	41603.0	39343.8	36794.7	36348.8	37158.8	37680.2	39435.2	42737.5	45275.4	46522.0	44498.9	42053.3	40787.6
1974	39679.8	37256.0	34916.0	34525.0	36605.8	37516.0	39488.7	42534.0	45435.8	45221.4	43438.5	41676.8	39857.8
1975	39586.1	37134.2	34668.7	33517.1	35109.6	37277.8	38506.2	44492.4	47145.8	48022.4	46657.0	44904.1	40585.1
1976	42965.4	40650.2	38632.1	38420.4	39988.5	40570.7	42171.4	44785.1	44940.7	44901.3	43604.2	41235.5	41905.5
1977	38825.3	36490.3	34604.8	33650.4	34076.8	35926.6	37109.6	40435.0	41662.4	42215.4	40823.6	39035.9	37904.7
1978	37158.2	35481.9	33980.0	33861.5	32282.9	33038.3	34844.9	38714.3	40272.5	42114.8	41197.7	39438.6	36865.5
1979	38162.8	36730.6	34899.8	35117.0	37151.6	40492.1	43497.4	45543.4	47505.1	48060.4	47075.6	44334.4	41547.5
1980	41706.7	39085.6	36902.5	35151.4	37645.7	39760.1	42924.4	46390.2	48092.3	49784.0	48841.3	45880.3	42680.4
1981	42908.4	40666.6	38596.5	37089.9	37735.7	40846.7	44141.8	48973.5	52000.5	51338.8	49694.4	46112.0	44175.4
1982	43473.7	40688.8	38052.6	36567.4	37173.5	39397.6	39927.2	41078.7	42334.8	43589.2	41954.7	39986.4	40352.1
1983	37971.9	36177.9	34477.6	33433.1	33491.2	35402.5	36645.4	39157.8	40833.2	42142.3	41274.6	39145.3	37512.7
1984	36936.7	35229.2	33514.2	33904.4	34977.4	35793.7	39054.8	40022.4	41380.7	40786.9	40173.7	38108.2	37490.2
1985	36412.1	34552.5	34689.7	35285.3	36970.8	38043.1	38808.8	39728.0	41424.8	42105.8	41321.5	39245.1	38215.6
1986	37075.5	36318.7	34561.0	34375.4	34379.6	36348.6	38388.5	39705.8	40937.5	42240.1	41229.9	39347.0	37909.0
1987	36778.0	34518.7	32232.0	31859.4	33351.1	33900.5	33360.0	33717.2	34644.0	34936.4	35239.6	33513.7	34004.2
1988	31892.5	30578.8	29286.3	28645.4	29719.1	30963.3	33864.1	36398.6	39689.1	40471.0	39837.2	39016.3	34196.8
1989	37579.7	36166.4	36669.7	36140.6	36565.0	38316.3	40518.3	42635.7	44415.4	45211.0	46426.1	45010.9	40471.3
1990	43263.0	41864.8	40572.0	39113.5	39047.8	38056.8	39967.7	42918.1	44598.8	45932.3	45356.8	43853.4	42045.4
1991	42065.3	40870.5	37977.8	37702.2	38051.5	38748.8	41303.5	43724.3	44207.5	46154.9	46308.3	44943.3	41838.1
1992	42262.7	40938.5	40051.2	40727.6	41670.6	41851.1	43579.7	47343.3	48535.6	50066.5	49645.5	47524.6	44516.4
1993	44717.0	42884.8	42184.2	43903.1	44396.0	45540.9	46895.7	46160.1	47189.7	46981.0	46327.7	44720.0	45158.4
1994	42691.3	40879.3	40792.2	41399.4	42994.6	44961.3	46776.3	47952.2	49205.8	50179.2	49497.0	46685.1	45334.5
1995	43839.3	41728.5	41096.6	40241.2	41612.8	41001.3	42446.1	42609.9	44120.8	45567.8	44150.5	42263.7	42556.5
1996	39999.6	38067.7	37962.3	39304.7	40681.9	41916.2	43311.8	42191.9	44311.2	46220.3	45366.3	43324.2	41888.2
1997	41179.3	39236.3	37833.0	39964.3	40086.6	40596.5	41385.0	42161.0	42520.1	46234.1	47014.8	46212.1	42035.3
1998	44297.1	42306.8	40797.4	41994.0	42240.3	44614.9	47562.0	48585.4	48732.1	52077.0	52262.2	49026.5	46208.0
1999	46159.1	43478.4	41882.9	44308.0	45293.8	48487.7	50005.3	52848.5	55713.9	59073.2	57404.1	53739.3	49866.2
2000	50779.5	47974.4	45214.1	44272.9	44361.8	46023.3	48636.6	50643.0	52174.6	52508.8	52230.0	52145.4	48913.7
2001	49603.6	46916.5	45054.0	42572.6	41300.4	43225.4	44660.9	47138.6	49948.8	51433.4	51922.8	52291.3	47172.4
2002	49339.3	45898.0	43210.4	43330.9	42226.7	42929.6	43543.6	45450.7	47105.9	49203.5	47443.7	47537.1	45601.6
2003	44819.8	42603.6	38796.7	36571.4	36493.7	39121.0	42320.5	43282.1	44833.3	44812.4	46755.5	44405.9	42068.0

2004	41916.9	39704.9	36815.5	35194.5	34930.8	36164.2	38039.9	39382.2	40992.7	42316.2	43914.6	43408.6	39398.4
2005	41391.6	38369.0	35545.7	33264.9	33998.4	35350.5	36284.8	39402.9	40306.7	41639.9	40618.7	40007.8	38015.1
2006	37949.1	36067.3	34075.8	34091.2	35077.2	37054.2	38233.7	39594.3	40666.6	42278.8	42860.4	42658.6	38383.9
2007	40865.2	38544.3	36102.4	36729.3	37652.3	39519.2	42618.9	44818.5	47342.8	47807.2	47381.6	44548.5	41994.2
2008	42243.2	39650.6	37086.1	37046.9	37379.9	37020.8	37862.0	39408.4	42733.8	44770.0	44671.0	42218.0	40174.2
2009	41856.7	40689.3	38898.9	41289.3	40531.9	40279.4	41580.1	44432.9	47261.5	47920.7	47751.2	45651.7	43178.6
Total	2280764.7	2167983.1	2080048.3	2057724.9	2092963.8	2167303.6	2275992.5	2417342.1	2523646.0	2594610.8	2550348.5	2445239.9	2304497.4
Max	58613.9	56043.5	52403.4	52889.0	53076.6	53736.3	55166.9	59165.8	62288.0	65260.6	62565.5	60169.5	57183.1
Min	17352.4	16412.5	15669.2	15117.0	15024.5	15455.1	17242.4	18246.9	19188.8	20093.5	19329.7	18545.6	17705.6
Mean	38012.7	36133.1	34667.5	34295.4	34882.7	36121.7	37933.2	40289.0	42060.8	43243.5	42505.8	40754.0	38408.3
Stdev	11885.7	11352.9	10326.8	10258.0	10343.9	10489.7	10839.5	11381.4	11831.7	12111.3	11889.7	11403.9	11032.6
CV	31.3	31.4	29.8	29.9	29.7	29.0	28.6	28.2	28.1	28.0	28.0	28.0	28.7

Appendix C. 5: Flooding Volume of Sudd Swamp result from Thronthwiate Evaporation Million m3

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	0	0	15500	15998.55	16548.4	18633.71	20567.27	23034.98	23691.51	24608.02	22559.61	20028.09	15624.63
1951	18054.81	15860.06	13292.97	11863.31	11331.25	11399.99	12784.52	14253.36	14588.15	15055.72	14234.7	12840.65	12885.42
1952	11104.51	9907.402	9152.396	8870.57	9525.093	9947.912	10959.92	13118.7	14393	15444.7	15166.51	13842.84	11029.66
1953	12854.83	11088.06	9483.068	8643.72	8925.702	10186.61	11679.81	13339.38	13463.7	13951.14	13159.87	11739.39	10805.25
1954	10209.41	8613.832	7445.862	7274.203	7555.712	8069.82	9789.724	11291.27	12768.36	13051.77	12471.27	11985.72	9421.611
1955	10602.77	9121.119	8282.893	8332.13	8223.365	8521.28	9230.361	10509.06	12279.7	12584.26	11979.73	11581.41	9477.16
1956	11677.1	10300.37	9053.042	9045.322	8970.014	9674.045	10883.92	13809.08	14844.3	15608.99	14281.22	13537.79	11049.32
1957	12987.33	11798.55	11018.2	10267.15	10686.56	11761.46	13162.37	15199.61	15437.22	15237.82	14388.92	12598.21	12038.49
1958	10563.93	9336.833	7861.62	7299.942	7148.044	8359.579	9412.252	10330.24	11554.18	12385.3	11785.37	10656.14	9127.032
1959	9421.645	8338.602	7194.073	6758.823	7043.641	7197.066	8043.283	9319.95	10410.23	11105.69	10814.83	10037.18	8280.309
1960	9184.075	7917.883	6964.184	7290.107	7279.315	7668.381	8661.337	9749.468	10576.14	11332.57	10791.81	9990.993	8412.79
1961	9268.235	8748.96	7821.536	7219.268	7171.087	7528.974	9291.546	10648	12044.78	13790.38	14535.89	14809.09	9602.982
1962	15345.35	15686.3	15757.2	15827.27	16502.72	17982.14	20177.85	23153.04	25968.75	28151.76	27173.75	25757.92	19188.16
1963	24298.96	22971.48	21935.28	22935.63	24020.2	27082.7	29810.51	34562.97	37357.74	37719.18	37391.79	34372.93	27417.1
1964	30871.26	28259.73	25564.7	25254.9	26586.35	27238.53	31673.11	36831.74	40775.38	43643.34	41897.35	40281.89	30834.02
1965	38398.65	35112.91	30501.01	30702.52	30619.59	31391.54	33650.48	37351.6	39779.21	40976.47	38641.13	34970.83	32620.07
1966	30814.29	28463.4	27697.33	27396.32	27542.12	28170.79	30810.6	34071.52	36707.68	39166.9	36444.16	32733.77	29383.45
1967	29527.63	27044.21	24680.26	22419.06	22270.84	23569.83	26758.62	30131.88	32977.87	34525.36	34682.08	32460.61	26385.79

1968	30512.39	28341.84	25869.74	24553.45	23885.44	25676.44	27828.97	31950.47	33053.41	34148.01	32529.33	30377.88	26976.57
1969	27864.05	25751.48	24979.28	23804.76	23920.87	25002.87	27497.8	30782.92	32626.09	33198.11	31929.94	28783.53	26008.52
1970	26003.15	22753.36	21170.66	20595.18	20077.83	21235.54	23612.89	26942.38	29198.79	30793.46	29959.36	29926.03	23402.97
1971	29093.13	27058.1	23331.98	22250.62	23762.36	23964.08	26804.84	30627.48	32485.83	32984.39	31027.77	29608.38	25766.92
1972	26399.13	23537.36	19968.33	19549.7	19512.74	20132.99	21802.43	24363.64	25378.49	25710.45	24327.43	21620.5	21098.09
1973	19123.25	16943.04	15110.09	15276.66	15773.78	16425.37	18255.22	21224.68	23268.62	24085.48	22695.91	20692.31	17757.49
1974	18953.02	16701.79	15076.71	15280.49	16562.31	17417.41	19516.59	22236.64	24687.06	24944.42	23752.87	22493.1	18430.49
1975	20768.63	18215.98	16236.03	15649.45	16419.11	18041.8	19601.92	24516.91	26660.34	27318.21	26072.95	24762.96	19710.71
1976	23134.61	20752.93	18898.63	18872.83	19956.24	20711.22	22688.65	25204.05	25743.13	25796.9	24534.42	21860.82	20779.26
1977	19682.76	17465.53	15887.86	15536.09	15702.79	17077.03	18716.88	21613.01	22874.28	23477.06	22434.58	20582.59	17925.19
1978	18967.36	17494.48	16480.61	16136.03	14797.79	15460.47	17315.35	20498.52	21940.55	23184.02	22704.72	20955.8	17531.82
1979	19936.81	18194.57	16790.83	17105.05	18584.58	21203.01	24297.97	26840.41	28611.1	29003.79	27817.55	24857.92	21170.97
1980	22051.15	18716.69	17041.93	16180.54	17815.19	19461.82	22361.61	25446.91	26806.75	27721.72	26732.09	24244.38	20504.67
1981	21432.75	19445.93	17958.22	17080.64	17450.12	19594.06	22466.21	26126.44	28298.55	27697.83	26054.05	22497.95	20621.83
1982	20517.57	18259.91	16729.76	16052.11	16455.34	18048.8	19160.15	20550.1	21740.65	22804.85	22096.04	20952.69	18103.84
1983	19501.81	18096.01	17196.81	16702.96	16649.2	18042.65	19637.87	22031.11	23561.23	24610.35	23492.64	21565.11	18697.75
1984	19726.64	18616.53	17605.22	17998.05	18683.99	19522.2	22482.7	24022.55	25527.66	25480.49	24478	22026.77	19858.06
1985	20233.25	18558.38	18311.23	18550.25	19499.84	20215.81	21475.14	22785.27	24477.75	25277.78	24029.8	21973.66	19797.94
1986	19960.25	19100.09	17118.94	16665.25	16806.44	18362.18	20365.58	21973.42	23178.26	24425.49	23808.24	22395.97	18934.32
1987	19933.56	17702.08	15700.49	15587.75	16484.62	17150.62	17643.19	18541.89	19674.97	20385.81	20765.72	19206.47	16981.86
1988	17839.92	16648.16	15719.52	14987.27	15748.71	16786.74	19426.07	21795.61	24535.01	25235.15	24261.14	23168.9	18318.48
1989	22510.74	21339.91	21226.14	20048.03	19369.31	20743.31	22976.1	25181.47	26924.44	27814.45	28671.19	27894.91	22053
1990	26278.52	24229.87	22494.13	20983.97	20725.37	20647.24	22736.24	25538.42	27335.59	28665.65	27799.34	26164.16	22737.58
1991	24038.71	22619.55	19760.28	18679.33	18389.48	18826.68	21204.92	23434.92	24204.51	25802.43	25884.02	25020.96	20758.21
1992	21624.79	20216.54	20128.26	20954.88	21772.77	22372.54	24454.51	27832.76	29148.69	30256.22	29415.91	26564.48	22825.72
1993	22938.63	20648.21	19934.32	21118.58	21526.61	22591.06	24274.85	24889.78	25862.39	25999.38	25004.67	23776.01	21581.35
1994	21854.65	19511.32	19286.89	19801.14	20703.94	22215.91	24123.93	25682.86	26684.11	27504.75	27327.6	24229.45	21609.27
1995	21307.13	19315.39	18326.61	18100.39	18887.81	19169.77	20865.36	21805.94	22952.41	24064.32	22544.53	21424.31	19289.15
1996	19542.75	17990.38	17885.33	18872.18	19784.01	20842.95	22572.82	22837.11	24548.61	25885.13	25450.61	23562.24	20136.16
1997	21402.3	19830.85	18825.54	20556.15	20802.18	21875.35	23306.56	24733.1	25438.02	28236.75	27986.13	27153.85	21703.37
1998	24630.62	22613.64	21166.79	22227	22689.88	24890.83	27853.12	29634.2	30312.18	32759.23	32618.28	28651.15	24772.69
1999	25670.15	22714.12	21349.36	23307.78	23903.49	26233.55	28135.33	30918.51	33328.05	35858.01	34259.69	30034.96	25977.85
2000	27262.91	24523.48	22071.02	21342.66	21131.63	22308.97	24919.64	27191.7	28670.65	29357.1	28551.95	27781.52	23624.09
2001	26159.38	23456.88	21254.7	19615.79	18565.88	20057.66	21870.93	24235	26491.39	27769.85	27920.69	27062.43	22035.51

2002	25006.16	21453.69	19366.66	19600.85	18645.84	19416.05	20544.61	22551.71	24097.65	25853.15	24705.72	24421.24	20589.64
2003	21806.82	19498.48	16565.85	14909.81	14642.61	16324.03	18975.44	20272.19	21723.02	21897.44	23126.49	21596.85	17949.39
2004	19755.86	18409.54	16101.84	15842.4	15755.03	16787.03	18797.9	20550.13	22127.96	23247.78	24061.84	23114.41	18196.59
2005	21454.1	17622.75	15353.27	13975.11	14620.46	15800.92	17317.07	20166.26	21409.04	22799.01	21957.41	20526.66	17308.24
2006	18226.22	16192.73	15184.78	15040.85	15754.39	17180.29	18701.33	20417.45	21665.11	23059.68	23468.82	23242.29	17703.07
2007	21741.03	19256.19	16996.58	17052.09	17310.32	18696.87	21416.96	23631.94	25764.36	26306.29	25711.61	23183.79	19928.85
2008	20921.67	18671.62	16544.36	16511.26	16642.49	16729.94	17688.05	19536.31	22216.1	23990.02	23798.81	21617.06	18221.21
2009	20544.78	18812.06	17660.02	19617.27	19318.79	19518.29	21138.51	23838.72	26279.91	27026.68	26349.72	23764.85	20452.2
Total	1231498	1115851	1039871	1025971	1043442	1107147	1224180	1365661	1461131	1520776	1474520	1369567	1161414
Max	38398.65	35112.91	30501.01	30702.52	30619.59	31391.54	33650.48	37351.6	40775.38	43643.34	41897.35	40281.89	32620.07
Min	9184.075	7917.883	6964.184	6758.823	7043.641	7197.066	8043.283	9319.95	10410.23	11105.69	10791.81	9990.993	8280.309
Mean	20524.96	18597.52	17331.19	17099.52	17390.69	18452.45	20402.99	22761.01	24352.18	25346.27	24575.33	22826.11	19356.9
Stdev	6609.571	6115.993	5239.851	5283.186	5341.222	5545.475	6016.178	6633.555	7034.292	7292.612	7035.85	6543.678	5574.269
CV	32.20259	32.88607	30.23365	30.89668	30.71311	30.05279	29.48674	29.14438	28.88568	28.77193	28.62973	28.66751	28.79732

Appendix C. 6: Flooding Volume of Sudd Swamp result from Hamon Evaporation Million m3

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1950	0	0	15500	15998.55	16548.4	18633.71	20567.27	23034.98	23691.51	24608.02	22559.61	20028.09	16764.18
1951	18054.81	15860.06	13292.97	11863.31	11331.25	11399.99	12784.52	14253.36	14588.15	15055.72	14234.7	12840.65	13796.62
1952	11104.51	9907.402	9152.396	8870.57	9525.093	9947.912	10959.92	13118.7	14393	15444.7	15166.51	13842.84	11786.13
1953	12854.83	11088.06	9483.068	8643.72	8925.702	10186.61	11679.81	13339.38	13463.7	13951.14	13159.87	11739.39	11542.94
1954	10209.41	8613.832	7445.862	7274.203	7555.712	8069.82	9789.724	11291.27	12768.36	13051.77	12471.27	11985.72	10043.91
1955	10602.77	9121.119	8282.893	8332.13	8223.365	8521.28	9230.361	10509.06	12279.7	12584.26	11979.73	11581.41	10104.01
1956	11677.1	10300.37	9053.042	9045.322	8970.014	9674.045	10883.92	13809.08	14844.3	15608.99	14281.22	13537.79	11807.1
1957	12987.33	11798.55	11018.2	10267.15	10686.56	11761.46	13162.37	15199.61	15437.22	15237.82	14388.92	12598.21	12878.62
1958	10563.93	9336.833	7861.62	7299.942	7148.044	8359.579	9412.252	10330.24	11554.18	12385.3	11785.37	10656.14	9724.451
1959	9421.645	8338.602	7194.073	6758.823	7043.641	7197.066	8043.283	9319.95	10410.23	11105.69	10814.83	10037.18	8807.085
1960	9184.075	7917.883	6964.184	7290.107	7279.315	7668.381	8661.337	9749.468	10576.14	11332.57	10791.81	9990.993	8950.522
1961	9268.235	8748.96	7821.536	7219.268	7171.087	7528.974	9291.546	10648	12044.78	13790.38	14535.89	14809.09	10239.81
1962	15345.35	15686.3	15757.2	15827.27	16502.72	17982.14	20177.85	23153.04	25968.75	28151.76	27173.75	25757.92	20623.67
1963	24298.96	22971.48	21935.28	22935.63	24020.2	27082.7	29810.51	34562.97	37357.74	37719.18	37391.79	34372.93	29538.28
1964	30871.26	28259.73	25564.7	25254.9	26586.35	27238.53	31673.11	36831.74	40775.38	43643.34	41897.35	40281.89	33239.86
1965	38398.65	35112.91	30501.01	30702.52	30619.59	31391.54	33650.48	37351.6	39779.21	40976.47	38641.13	34970.83	35174.66
1966	30814.29	28463.4	27697.33	27396.32	27542.12	28170.79	30810.6	34071.52	36707.68	39166.9	36444.16	32733.77	31668.24

1967	29527.63	27044.21	24680.26	22419.06	22270.84	23569.83	26758.62	30131.88	32977.87	34525.36	34682.08	32460.61	28420.69
1968	30512.39	28341.84	25869.74	24553.45	23885.44	25676.44	27828.97	31950.47	33053.41	34148.01	32529.33	30377.88	29060.61
1969	27864.05	25751.48	24979.28	23804.76	23920.87	25002.87	27497.8	30782.92	32626.09	33198.11	31929.94	28783.53	28011.81
1970	26003.15	22753.36	21170.66	20595.18	20077.83	21235.54	23612.89	26942.38	29198.79	30793.46	29959.36	29926.03	25189.05
1971	29093.13	27058.1	23331.98	22250.62	23762.36	23964.08	26804.84	30627.48	32485.83	32984.39	31027.77	29608.38	27749.91
1972	26399.13	23537.36	19968.33	19549.7	19512.74	20132.99	21802.43	24363.64	25378.49	25710.45	24327.43	21620.5	22691.93
1973	19123.25	16943.04	15110.09	15276.66	15773.78	16425.37	18255.22	21224.68	23268.62	24085.48	22695.91	20692.31	19072.87
1974	18953.02	16701.79	15076.71	15280.49	16562.31	17417.41	19516.59	22236.64	24687.06	24944.42	23752.87	22493.1	19801.87
1975	20768.63	18215.98	16236.03	15649.45	16419.11	18041.8	19601.92	24516.91	26660.34	27318.21	26072.95	24762.96	21188.69
1976	23134.61	20752.93	18898.63	18872.83	19956.24	20711.22	22688.65	25204.05	25743.13	25796.9	24534.42	21860.82	22346.2
1977	19682.76	17465.53	15887.86	15536.09	15702.79	17077.03	18716.88	21613.01	22874.28	23477.06	22434.58	20582.59	19254.2
1978	18967.36	17494.48	16480.61	16136.03	14797.79	15460.47	17315.35	20498.52	21940.55	23184.02	22704.72	20955.8	18827.98
1979	19936.81	18194.57	16790.83	17105.05	18584.58	21203.01	24297.97	26840.41	28611.1	29003.79	27817.55	24857.92	22770.3
1980	22051.15	18716.69	17041.93	16180.54	17815.19	19461.82	22361.61	25446.91	26806.75	27721.72	26732.09	24244.38	22048.4
1981	21432.75	19445.93	17958.22	17080.64	17450.12	19594.06	22466.21	26126.44	28298.55	27697.83	26054.05	22497.95	22175.23
1982	20517.57	18259.91	16729.76	16052.11	16455.34	18048.8	19160.15	20550.1	21740.65	22804.85	22096.04	20952.69	19447.33
1983	19501.81	18096.01	17196.81	16702.96	16649.2	18042.65	19637.87	22031.11	23561.23	24610.35	23492.64	21565.11	20090.65
1984	19726.64	18616.53	17605.22	17998.05	18683.99	19522.2	22482.7	24022.55	25527.66	25480.49	24478	22026.77	21347.57
1985	20233.25	18558.38	18311.23	18550.25	19499.84	20215.81	21475.14	22785.27	24477.75	25277.78	24029.8	21973.66	21282.35
1986	19960.25	19100.09	17118.94	16665.25	16806.44	18362.18	20365.58	21973.42	23178.26	24425.49	23808.24	22395.97	20346.68
1987	19933.56	17702.08	15700.49	15587.75	16484.62	17150.62	17643.19	18541.89	19674.97	20385.81	20765.72	19206.47	18231.43
1988	17839.92	16648.16	15719.52	14987.27	15748.71	16786.74	19426.07	21795.61	24535.01	25235.15	24261.14	23168.9	19679.35
1989	22510.74	21339.91	21226.14	20048.03	19369.31	20743.31	22976.1	25181.47	26924.44	27814.45	28671.19	27894.91	23725
1990	26278.52	24229.87	22494.13	20983.97	20725.37	20647.24	22736.24	25538.42	27335.59	28665.65	27799.34	26164.16	24466.54
1991	24038.71	22619.55	19760.28	18679.33	18389.48	18826.68	21204.92	23434.92	24204.51	25802.43	25884.02	25020.96	22322.15
1992	21624.79	20216.54	20128.26	20954.88	21772.77	22372.54	24454.51	27832.76	29148.69	30256.22	29415.91	26564.48	24561.86
1993	22938.63	20648.21	19934.32	21118.58	21526.61	22591.06	24274.85	24889.78	25862.39	25999.38	25004.67	23776.01	23213.71
1994	21854.65	19511.32	19286.89	19801.14	20703.94	22215.91	24123.93	25682.86	26684.11	27504.75	27327.6	24229.45	23243.88
1995	21307.13	19315.39	18326.61	18100.39	18887.81	19169.77	20865.36	21805.94	22952.41	24064.32	22544.53	21424.31	20730.33
1996	19542.75	17990.38	17885.33	18872.18	19784.01	20842.95	22572.82	22837.11	24548.61	25885.13	25450.61	23562.24	21647.84
1997	21402.3	19830.85	18825.54	20556.15	20802.18	21875.35	23306.56	24733.1	25438.02	28236.75	27986.13	27153.85	23345.56
1998	24630.62	22613.64	21166.79	22227	22689.88	24890.83	27853.12	29634.2	30312.18	32759.23	32618.28	28651.15	26670.58
1999	25670.15	22714.12	21349.36	23307.78	23903.49	26233.55	28135.33	30918.51	33328.05	35858.01	34259.69	30034.96	27976.08
2000	27262.91	24523.48	22071.02	21342.66	21131.63	22308.97	24919.64	27191.7	28670.65	29357.1	28551.95	27781.52	25426.1
2001	26159.38	23456.88	21254.7	19615.79	18565.88	20057.66	21870.93	24235	26491.39	27769.85	27920.69	27062.43	23705.05

2002	25006.16	21453.69	19366.66	19600.85	18645.84	19416.05	20544.61	22551.71	24097.65	25853.15	24705.72	24421.24	22138.61
2003	21806.82	19498.48	16565.85	14909.81	14642.61	16324.03	18975.44	20272.19	21723.02	21897.44	23126.49	21596.85	19278.25
2004	19755.86	18409.54	16101.84	15842.4	15755.03	16787.03	18797.9	20550.13	22127.96	23247.78	24061.84	23114.41	19545.98
2005	21454.1	17622.75	15353.27	13975.11	14620.46	15800.92	17317.07	20166.26	21409.04	22799.01	21957.41	20526.66	18583.5
2006	18226.22	16192.73	15184.78	15040.85	15754.39	17180.29	18701.33	20417.45	21665.11	23059.68	23468.82	23242.29	19011.16
2007	21741.03	19256.19	16996.58	17052.09	17310.32	18696.87	21416.96	23631.94	25764.36	26306.29	25711.61	23183.79	21422.34
2008	20921.67	18671.62	16544.36	16511.26	16642.49	16729.94	17688.05	19536.31	22216.1	23990.02	23798.81	21617.06	19572.31
2009	20544.78	18812.06	17660.02	19617.27	19318.79	19518.29	21138.51	23838.72	26279.91	27026.68	26349.72	23764.85	21989.13
Total	1231498	1115851	1039871	1025971	1043442	1107147	1224180	1365661	1461131	1520776	1474520	1369567	1248301
Max	38398.65	35112.91	30501.01	30702.52	30619.59	31391.54	33650.48	37351.6	40775.38	43643.34	41897.35	40281.89	35174.66
Min	9184.075	7917.883	6964.184	6758.823	7043.641	7197.066	8043.283	9319.95	10410.23	11105.69	10791.81	9990.993	8807.085
Mean	20524.96	18597.52	17331.19	17099.52	17390.69	18452.45	20402.99	22761.01	24352.18	25346.27	24575.33	22826.11	20805.02
Stdev	6609.571	6115.993	5239.851	5283.186	5341.222	5545.475	6016.178	6633.555	7034.292	7292.612	7035.85	6543.678	6038.3
CV	32.20259	32.88607	30.23365	30.89668	30.71311	30.05279	29.48674	29.14438	28.88568	28.77193	28.62973	28.66751	29.02328