The effects of Jonglei Canal operation scenarios on the Sudd swamps in Southern Sudan

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Preface

In front you will find my master thesis about the effects of the implementation of Jonglei Canal scenarios on the Sudd swamps in Southern Sudan. This thesis is made as the completion of the master study Civil Technology & Management at the Twente University.

During my education I got more and more interested in the water management part of my study. Especially the hydrology side of this part got my interest. When I needed to find an assignment for my master thesis, my eye fell on the Nile catchment with it complex hydrology of the Sudd area. A chance I couldn't resist.

First of all I would like to thank my advisor from Deltares, prof. ir. E. (Eelco) van Beek. He gave me the opportunity to start with my master study in Delft. Although I couldn't finish my master thesis there due to some health problems, I had a great experience being there and had a good work social environment and nice colleagues. My advisor at the UT, dr. M.S. (Maarten) Krol, I would like to thank for his detailed feedback and his support during my graduation process. At last, I would to thank PhD Y.A. (Yasir) Mohamed, for his help and ideas for my master thesis due to his great knowledge about the area.

Erwin Lamberts

Summary

The Sudd, one of the largest wetland areas in the world, is faced by huge evapotranspiration rates. More than 50 % of the Sudd inflow is evaporated out of the Sudd swamps, resulting in less water availability in the downstream areas. To gain extra water downstream, planners have proposed to dig a canal (Jonglei canal) around to Sudd area, to save an extra 4.8 Gm^3/year. What the effects of the swamps in the Sudd area will be, are still relatively unknown. In this thesis the effects on the Sudd swamp will be studied based on several Jonglei Canal scenarios.

In the first phase of the study the historical monthly water balance for the period 1961 – 2000 has been simulated. This is done by creating a hydrological model based on the water balance made by Sutcliffe & Parks (1987). This model describes the Sudd as a reservoir, where the input comes from the precipitation and the inflow, and the output from the evapotranspiration and the outflow.

To simulate the water balance, several data sets had to be collected. The first data set is the precipitation data in the Sudd area. This data was collected at the Global Precipitation Climatology Centre (GPCC). The next data set is the evapotranspiration data. This data was simulated with the use of the ET_0 calculator (FAO, 2009). The ET_0 calculator uses the Penman-Monteith equation for the calculation of the evapotranspiration. The input for the calculator is collected at the measurement stations at Juba and Malakal for the temperature, relative humidity and the sunshine hours. The inflow data set is collected at the measurement stations Mongalla simulated in the RIBASIM model. The RIBASIM model simulates the monthly water flows for several measurement stations in the Nile basin. The outflow for the Sudd is based on the flows at the stations Malakal and Doleib Hill. The outflow is described as the flow of Malakal minus the flow at Doleib Hill. The data for the period 1961 – 1983 has been measured and the data for the period 1983 – 2000 will be simulated by a regression equation between the flows at Malakal and Doleib Hill.

When all the data sets were collected, the historical water balance for the Sudd could be simulated. The results from the water balance show that the swamp sizes in the period 1961 – 1964 increased by almost 300 % from 15 Gm^2 to around 60 Gm^2. In the period 1965 – 1978 the swamp sizes recovers to around 42 Gm^3 where it slightly decreased to 35 Gm^2 until 1978. In the period 1979 – 1981 the swamps show a sudden size increase. This is caused by a high increase in the precipitation in that period. In the last period until 2000 the Sudd swamps fluctuates around 30 Gm^2.

The second phase of the study several Jonglei canal scenarios have been tested. The scenarios are placed in three groups: fixed canal flows, seasonal dependent canal flows and flows where the extra water volume downstream of the Sudd will be 4.8 Gm^3/year. For the simulation of the swamps with the canal flows some variables needed to be adjusted. The inflow will now be decreased by the flow through the canal. The evapotranspiration will change under influence from a changing relative humidity as a result of the drained area. At last the outflow will change. The Sudd outflow is linear related to the swamp area where there will be a division in a dry period relation and a wet period relation.

The results from the fixed canal flows show a high linear relation between the flows and the change in the permanent (16 – 26 %), seasonal (13 – 22 %) and total swamp (15 – 25 %). The effects on the permanent swamp will be the highest, followed by the total swamp and at last the seasonal swamp.

The effects with seasonal dependent canal flows will be the highest on the size of seasonal swamp. The change on the permanent swamp depends mainly on the total

yearly flow. When this total is high, the decrease of the permanent swamp will also be high. The change on the seasonal swamp depends on the size of the canal flow in the wet period. When this is high, the decrease of the seasonal swamp will also be high. The change on the total swamp depends, just like the permanent swamp, on the total yearly flow.

To create 4.8 Gm^3/year water downstream of the Sudd, the average canal flow need to be 18 Mm^3/day. The scenario, a canal flow of 10 Mm^3/day in the dry period and 26 Mm^3/day in the wet period, has the highest influence on the total swamp, almost 26 %. The same scenario has the highest influence on the seasonal swamp. The scenario, a canal flow of 26 Mm^3/day in the dry period and 10 Mm^3/day in the wet period, has the highest influence on the permanent swamp, although the difference between the scenarios is small.

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Introduction

1.1 General

The Sudd wetland is one of the largest wetland areas worldwide and is located along the Nile in southern Sudan between Mongalla in the south and Malakal in the north, covering an area of 500 km (north – south) and 200 km (east – west) (see Figure 1). The size of the wetland is variable, consisting of permanent swamps during the dry season (November until March) and seasonal swamps, created by flooding of the Nile (Bahr el Jebel), in the wet season (April until October). On average over the last 50 years the total swamp size consists 60 % of permanent swamps and 40 % of seasonal swamps (Sutcliffe & Parks, 1987). The annual pattern of flooding is an essential feature for the ecosystem of the area and is considered crucial to the local flora and fauna and to the way of life of the local people.

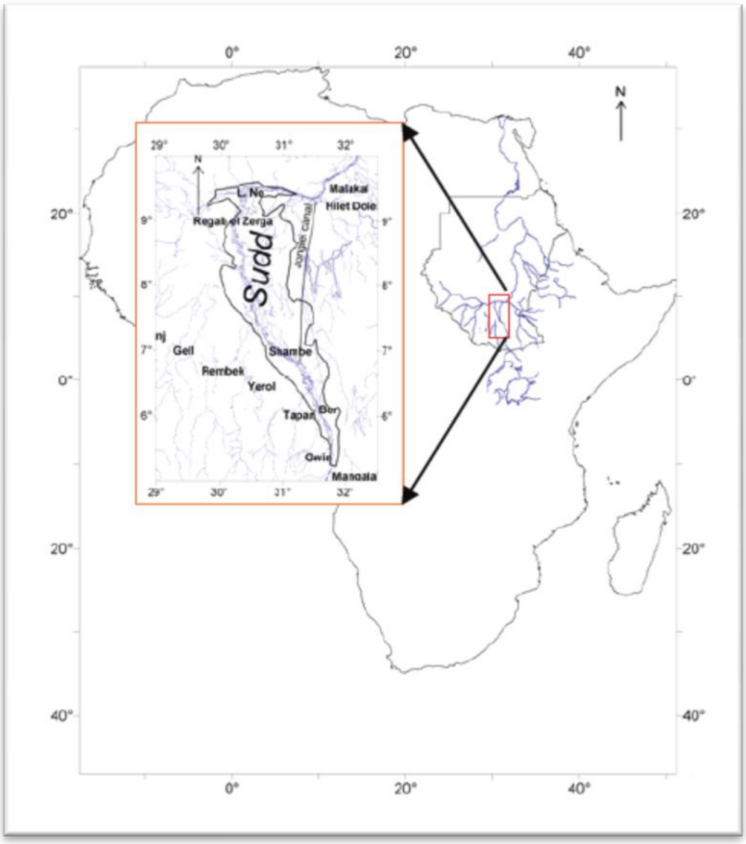

Figure 1 *The Sudd area within the Nile catchment*

The seasonal river flooded lands (toichs) are a yearly dynamic phenomenon caused by seasonality in the discharge of the Bahr el Jebel and the geomorphology of the area. The toichs are a vital component of the grazing cycle for the cattle and wildlife in particular the dry season. The permanent swamps, flooded throughout the year, are less economically valuable, though it is a refuge to wildlife. Wildlife migrates from high land during the rainy season to rain-flooded grasslands at the end of the rains. For the local people the livestock is an important part of the economy, and there is no alternative to the toichs in a grazing economy without recourse to irrigated grassland.

The Sudd wetland is characterized by huge evaporation which results in a lower water availability for the downstream areas. The evaporation from the Sudd is estimated to be more than 50 % of the Nile inflow into the Sudd near Mongalla, i.e. about 28 Gm^3/yr out of the 49 Gm^3/yr during the period 1961-1983.

To save extra water for use downstream the Sudd, hydrologists in the early part of the 20th century proposed digging a canal, the Jonglei Canal, east of the Sudd which would divert water from a point below Bor, to a point on the Sobat River, just above its confluence with the White Nile. The canal was planned to be 360 km long, 50 m wide and 4 m deep and will divert about 20 million m^3 of water per day around the swamps and will save about an extra 4.8 Gm^3/yr which is distributed equally between Sudan and Egypt. The canal will be navigable and will be constructed beside an all weather road, both of which will improve communications in the area. However, it is clear that the canal will bring about a diminution of the Sudd and a change in the distribution of the wetlands in the area.

The decision to construct the canal was made in 1974 by the Permanent Joint Technical Commission for Nile Waters (PJTC). The construction began in 1978, but the political instability in Sudan held up work after 1983. Until this day only 260 km of the total 360 km have been excavated. Several studies have been carried out to estimate the effects on the Sudd area when the Jonglei Canal would be completed, but until this day there aren´t many firm conclusions about the impact on the Sudd swamp.

1.2 Historical studies

Literature from different authors has been reviewed to obtain a picture on available information on the Sudd swamps. First comprehensive assessments of the Sudd hydrology are available from Hurst & Philips (1938) and Butcher (1938). Both authors described meteorological conditions, topography, hydrology and vegetation in the swamps and investigated the losses of half the inflowing waters which evaporated in the swamps.

In 1948, Penman assessed and established general methods to estimate evaporation in wetland areas. Detailed studies regarding this topic in the Sudd swamp were carried out by Migahid in 1948 and 1952, aiming at improving the understanding of the swamp vegetation and related evaporation losses.

With plans for the Jonglei Canal being brought forward, extensive assessments were carried out to investigate the Sudd, mainly focusing on the area between Mongalla and Bor. The Jonglei Investigation Team (JIT, 1954) carried out surveys providing a comprehensive account of the situation in the swamps, describing its topography, ecology, hydrology, inhabitants, agriculture and fisheries as well as the potential impacts of the planned canal scheme. Sutcliffe who was part of the investigation team extended this work, providing a detailed picture of the Sudd topography south of Bor and describing the flow, spill and flooding conditions in this area as well as ecological factors and the flood cycle dependency of the local economy. In various papers Sutcliffe provided further details of the southern Sudd hydrology (Sutcliffe, 1974) describing the flood process as flow along a series of basins down the floodplain. Sutcliffe & Parks (1987) further expanded the description of hydrological processes in the Sudd by establishing a mathematical model which was used to rout river flows and assess flood extents under different flow conditions based on water balance equations utilizing precipitation and evapotranspiration in combination with inflow and outflow data at Mongalla and Malakal respectively. River Sobat flow data as recorded at Doleib were subtracted from the Malakal flows in order to take them out of the equation, Bahr el Ghazal flows were considered to be of negligible influence. This model was further used to assess the effects of the by then stopped Jonglei Canal scheme on the flood extent under different flow conditions. Similar studies have been conducted by Mefit-Babtie (1983) and Howell *et al.* (1988).

As described above, the latest study that used a mathematical model to calculate the Sudd water balance was made in 1987 by Sutcliffe & Parks. Since that date there has been better knowledge and data (like remote sensing techniques), especially about the evatranspiration losses in the Sudd (Mohamed, 2005). Next, the water balance of the Sudd was represented in a model of the entire Nile basin, used for policy analysis at basin level (Ribasim, 2009); this model however was not applied in particular to assess effects on the Sudd. With this increased knowledge and with the availability of new data, there lies an opportunity to get a more accurate view of the water balance in the Sudd and the change in Sudd swamps.

In this study there will be made a monthly calculation of the water balance for the period 1961 – 2000 with the use of the existing hydrological model for the Sudd, created by Sutcliffe & Parks. The difference in this new calculation compared to Sutcliffe and Parks will be the extension of the water balance until 2000, the use of actual evapotranspiration instead of open water evaporation, and more accurate data for the precipitation in the Sudd area.

1.3 Problem analysis

The Nile discharges its water into the Sudd wetlands, a network of lakes, channels and swamps, which are characterized by high evaporation rates that have huge effects of the water availability in the areas direct downstream. The increased water demands of these areas, for particularly irrigation projects, forced planners to search for additional water flows by building short cut channels to bypass the Sudd wetland (e.g. the unfinished Jonglei Canal).

The Jonglei Canal should create positive effects in the downstream part of the Nile basin, but can create certain problems for people and flora and fauna in the Sudd area. The diversion of the water may most likely cause the Sudd swamps and associated floodplains to shrink which can give the following effects on the area:

I. The annual process of seasonal inundation from river flooded grasslands (toichs) produces species of grasses, that sustain the livestock and the wild life during the driest months of the year, can be interrupted *(effect on seasonal swamp)*.

II. A severe decrease in the discharge into the Sudd would cause the disappearance of many lakes in the papyrus zone which causes a serious loss of fishing in the area *(effect on permanent swamp)*.

III. The annual floods are crucial to the maintenance of biological diversity and the ecosystem in the Sudd *(effect on total swamp)*.

1.4 Research objective

The goal of this study is to analyze different operating rules of the Jonglei Canal with the use of a hydrological model to enhance water supply towards downstream while minimizing the effects on the change of the size and seasonal cycle of the Sudd. Operating the Jonglei Canal gives the opportunity to influence the dynamics of the Sudd area during the year by regulating the discharge through the canal.

1.5 Research question and criteria

The main research question of this study is how the Jonglei Canal can be regulated to minimize the above described effects of the implementation of the canal while increasing downstream water availability with a fixed amount. To answer this research question, several operating rules of the canal will be investigated.

The criteria for the most suitable operating rule will be as follow, where the Jonglei operating situation will be compared with the normal (no Jonglei Canal) situation:

1. What is the effect on the total, permanent and seasonal swamp size (Δkm^2)?
2. Will there be a change in the relation permanent/seasonal swamp size ($\Delta\%$)?
3. What will be the effect on the flows downstream the Sudd area (Δm^3)?

1.5 Approach of the study

The goal of this study is to get insight in the results from different Jonglei Canal scenarios on the change of the swamp size in the Sudd. To achieve this goal, the steps in figure 2 will be followed. In the diagram, the steps are numbered that need to be made to come to the final goal. The process is divided into seven steps:

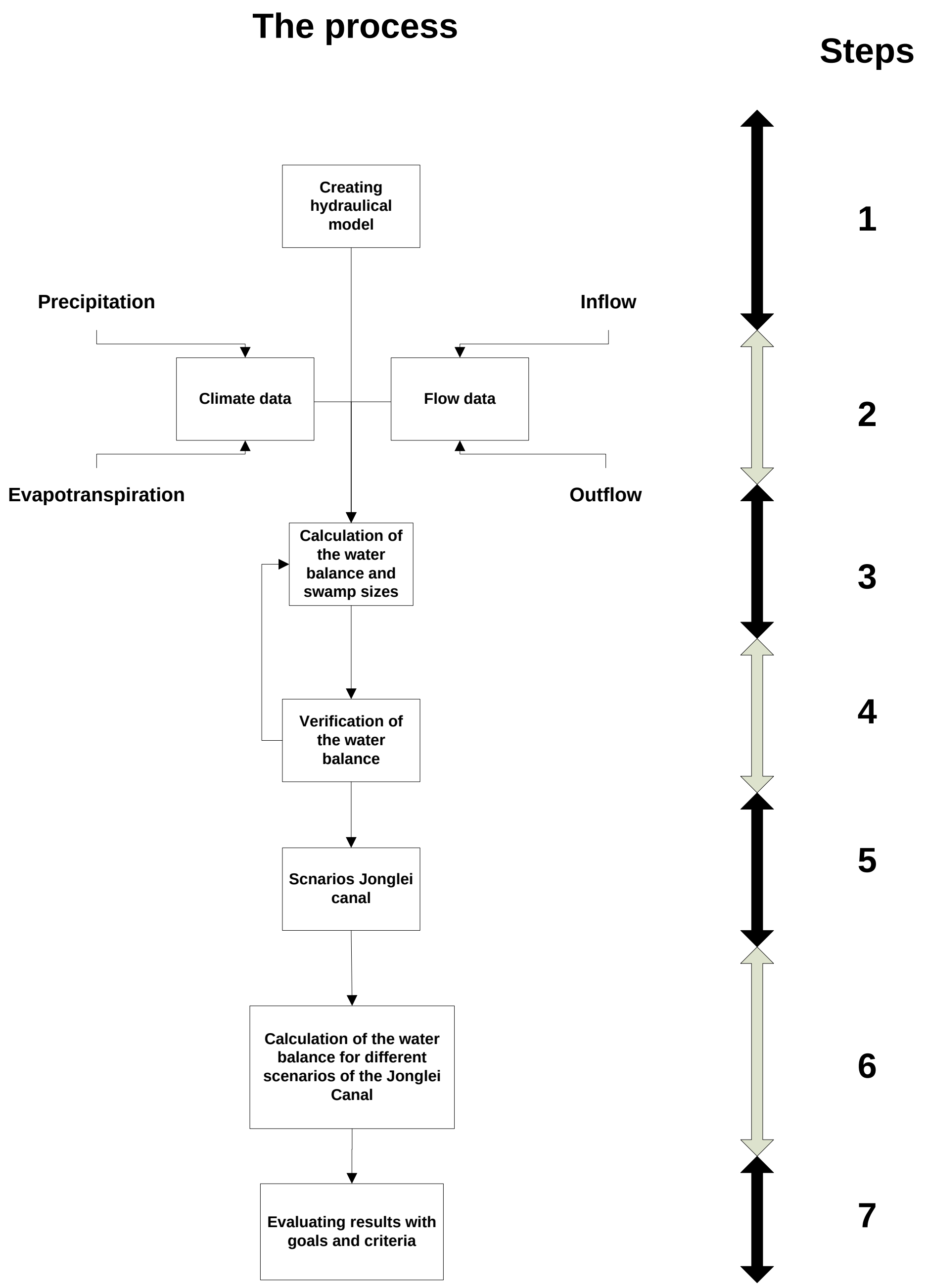

Figure 2 *The different steps that will be made during this study*

The description of the **7 steps**:

1 Creating the model, based on the hydrological model of Sutcliffe & Parks *(chapter 3)*

2 The collection of the monthly data in the Sudd area for the inflow, outflow, precipitation and evapotranspiration for the period 1961 – 2000 *(chapter 4,5,6 and 7)*

3 The monthly water balance will be simulated using the hydrological model for the water balance *(chapter 8.1)*

4 The simulated water balance c.q. swamp sizes will be verified with existing measured swamp sizes from satellite assessments *(chapter 8.2)*

5 Different scenarios for the Jonglei Canal will be created *(chapter 9.3)*

6 The created scenarios will be simulated *(chapter 9.4, 9.5 and 9.6)*

7 The results from the different Jonglei Canal scenarios will be compared to the goals and criteria *(chapter 9.7)*

With the completion of these steps the goal of the study will be achieved.

2. Description of the Sudd wetland

2.1 General

The Sudd wetland is one of the largest wetlands in the world and is located between 4,5° to 9,5°N and 29,5° to 31,5° E (Figure 1). The exact boundaries of the swamp are difficult to specify, because of its immense dimensions and inaccessibility of the area. Attempts to define its size are based on hydrological models, on remote sensing, or on both. The average area of the Sudd wetland is estimated between 30,000 and 40,000 km^2 (Sutcliffe & Parks, 1987). The wetland of the Sudd is composed of interconnected (sometimes parallel) river channels, associated with huge flood plains. The permanent swamps, usually close to the main river courses are permanently wet. However, substantial parts of the Sudd are seasonal swamps created by flooding of the Nile or when ponds are filled seasonally with rainwater (Howell et al., 1988).

2.2 Visualization

The permanent swamps of the Sudd begin at Mongalla where they are 10-13 km wide over a straight line distance of 115 km, until Bor. After Bor the swamps widen up to 25 km and with the peripheral floodplains even wider. Major channels occur to the east, and there are several large lakes enclosed by permanent swamps on both banks. At Zeraf Cuts two canals on the east bank join the main channel of the Bahr el Jebel with the Bahr el Zeraf, but only the southern canal is kept open. Here, water flows from the Bahr el Jebel to the Bahr el Zeraf, which reenters the Bahr el Jebel near Tonga and thus isolates Zeraf Island between the two rivers. This island, east of the Bahr el Jebel, 180 km long and up to 65 km wide, was once mostly dry land, but following the rise in water levels after the 1960s, it has become a seasonal floodplain. Meanwhile the seasonal floodplain on the west bank of the Bahr el Jebel is 25 km wide in places and at Lake No, 190 km due north of Zeraf Cuts, the Bahr el Jebel receives the Bahr el Ghazal. From Lake No, the river, now often known as the White Nile, swings abruptly eastwards for 115 km to a confluence with the Sobat River. It then flows northeastwards, past Malakal, having left the Sudd above the Sobat.

The evaporation map in figure 3 gives an estimation of the extension of the Sudd wetland, with the dark blue parts as the permanent swamp and the light blue/green parts the seasonal swamps.

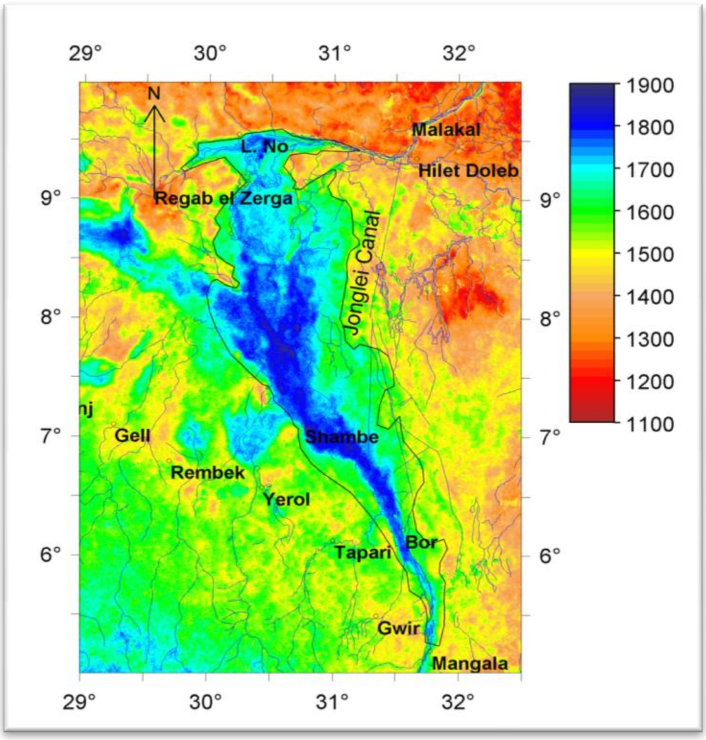

Figure 3 *The Sudd areas with his boundaries (Mohamed, 2006)*

2.3 Climate

The temperature in the Sudd varies from 30° - 33° during the dry season, dropping to an average of 18° in the wet season. Rain falls in a single season, lasting from April until November, with 850 mm/yr in the northern part to 950 mm/yr in the southern part. The relative humidity exceeds 80 % during the rainy season, and drops to below 50 % in the dry season (Mohamed et al, 2007). The evaporation rate in the Sudd area is investigated in several studies with different outcomes. Table 1 gives an overview of the different studies that were made that estimated the evaporation rates for an average year.

Evaporation (mm/year)	Source	Method
1533 (E_a)	Butcher, 1938	Measurements of papyrus grown in water tanks, aerial photo, water balance
2400 (E_a)	Migahid, 1948	Lysimeter experiment on the Sudd, close to Bahr el Zeraf cuts
2150 (E_o)	Sutcliffe and Parks, 1999	Penman formula, water balance
1636 (E_a)	Mohamed, 2005	Remote sensing and SEBAL
1951 (ET_0)	WL | Hydraulics et al, 2008	Penman-Monteith, Reference evapotranspiration

Table 1 *Different estimates of evaporation rates over the Sudd swamp for an average year (E_a = Actual evapotranspiration, E_0 = Open water evaporation, ET_0 = reference evapotranspiration) (Mohamed, 2005)*

2.4 Hydrological background

The inflow to the swamps combines the 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. Thus for half the year the flow at Mongalla depends on lake levels while the high flows between May and October mainly derive from local rainfall. Longer-term variations in East African lake levels and outflows have an important effect on the Mongalla flow. Because the average rainfall over Lake Victoria is almost equal to the evaporation, the lake system is sensitive to changes in rainfall and tributary inflow.

Below Mongalla the channel capacities are less than the flood flows and the alluvial channels themselves are above the flood plain. Thus excess flows leave the river through spill channels and inundate wide areas on either side of the river; this inundation is limited by higher ground only in the south of the swamps. The high flows coincide with the rainfall season within the swamps, when evaporation is comparatively low. The outflow from the swamps is relatively constant, with a very seasonal cycle, and roughly totals only half the inflow (Sutcliffe & Parks, 1987). The combined effect of these processes is that varying areas are inundated permanently or seasonally, with the uncovering of the seasonal swamp coinciding with the dry season. The areas of permanent swamp reflect the longer term variations in flow from the East African lakes, while the seasonal swamps depend on the torrent inflows and the annual cycle of balance between rainfall and evaporation within the swamps.

Sutcliffe (1974) described the reach between Juba and Bor, where the flood plain is incised and is divided into a number of basins which act as reservoirs in series, storing water when the river rises and returning water to the river downstream when it falls. Further north, the channel system becomes even more complex, with a number of channels parallel to the main river. However, there is no topographic limit to the flooding which extends further from the river in periods of high flow, especially to the

Northeast where there is a lack of defined channels and it is doubtful whether much of the spill returns to the main river. The flooding pattern is complex but may be described by a water balance model, where the swamp storage is represented by a reservoir.

2.5 Flora and fauna

The Sudd is one of the largest floodplains in Africa, providing watering and feeding grounds for populations of migratory mammals and birds. This floodplain borders the arid Sahelian region and is an important watering place for many species as they move across the landscape. The floodplain ecosystem supports a variety of plant species. Wild rice grassland dominates the seasonally inundated floodplains. This seems to suggest that rice may grow in the Sudd area. Improved rice varieties may grow in the floodplains in addressing poverty in Southern Sudan. During the 1980s Southern Sudan had among the highest population levels of antelope in Africa and the Sudd has been listed as a key location for the recovery of threatened antelope in Sub-Saharan Africa. Among the most abundant species found are the white-eared kob, the tiang and the Mongalla gazelle and these three species of antelopes make large-scale migration over the relatively undisturbed habitat of the Sudd. A million individuals of white-eared kob undertake a massive migration following the availability of floodplain grasses.

It is to be noted that the floodplains of the Sudd provide important habitat for several species of birds. The floodplains support the largest population of shoebill in Africa. The endangered white pelican flies over 2,000 kilometers from Eastern Europe and Asia to reach one of its most important wintering grounds on the floodplains of the Sudd. The Sudd is also a stronghold for the black crowned cranes, a species that has been designated vulnerable. Annual floods are crucial to the maintenance of biological diversity in the Sudd. The Dinka, Nuer and Shilluk (or Cholo) co-exist in the Sudd with tens of thousands of large herbivores depend on the annual floods and rain to regenerate floodplain grasses which feed their herds of cattle. Fishing in the Sudd is also a means of livelihood. (Howell et al, 1988)

The completion of the Jonglei canal project is likely to affect the bio diversity and ecosystem of the Sudd area as a result of the decreased water availability. At any rate it is seen that diversion of the water may most likely cause the Sudd swamps and associated floodplains to shrink dramatically, threatening the fauna and flora that depend on the swamps and floodplains for survival.

The Jonglei canal is also likely to have a significant impact on climate, groundwater recharges, silt and water quality. This involves the loss of fish habitat and grazing areas which in turn will have serious implications for the people of the area.

The seasonal river flooded lands (toichs) are a yearly dynamic phenomenon caused by the extreme variable rainfall in the area. The toichs are a vital component of the grazing cycle for the cattle and wildlife in particular the dry season (Howell et al, 1988). The permanent swamps, flooded throughout the year, are less economically valuable, though it is a refuge to wildlife. Wildlife migrates from high land during the rainy season to rain-flooded grasslands at the end of the rains. For the local people the livestock is an important part of the economy, and there is no alternative to the toichs in a grazing economy without recourse to irrigated grassland. It may be clear that the toichs are crucial to the economy at this time of year. It is however, just these grasslands that may be reduced by the operation of the canal.

3. Hydrological model

3.1 General

The water balance of the Sudd is represented by a hydrological model which uses partly measured/simulated inflows and outflows, estimates of precipitation and evaporation to reproduce volumes and areas of flooding over the historical period 1961 - 2001. Simulated outflows based on swamp areas are subsequently substituted for measured outflows so that the proposed diversions through the Jonglei Canal can be incorporated in the model in order to predict the effects of the canal on areas of flooding.

The flooding pattern of the Sudd 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 reach 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.

A hydrological study was carried out to analyze the historical behavior of the swamps and to estimate the effect of the canal on the areas of permanent and seasonal flooding.

3.2 The model

The Sudd swamp can be treated as a reservoir whose storage is dependent on inflow and outflow data, estimates of rainfall and evaporation data.

According Sutcliffe and Parks (1987) the Sudd water balance can be calculated using the equation of continuity for a time interval Δt:

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

where V is the volume of water stored in the flooded area (Gm^3), Q_{in} is the inflow (Mm^3/month), Q_{out} is the outflow (Mm^3/month), P is the precipitation (Mm^3/month) and E is the evaporation (Mm^3/month).

When Δt is taken as a monthly interval, the monthly change of volume of flooding can be calculated.

The average water depth of the Sudd has been estimated at 1.0 m (Sutcliffe & Parks, 1987). Several water depths have been studied, but a water depth of 1 m seems to give the most accurate simulation results. This leads to the assumption that the area of flooding A (m^2) is equal to the storage volume V (m^3), A = V.

The Sudd area is divided in two parts to give a better insight and more accurate results in the water balance. The two reasons for dividing the whole into two parts are:

- The difference in precipitation between the north and south part of the Sudd area are significant. When using the average rainfall over the whole area, the results of the water balance gives a wrong image of the change in storage volume and area of flooding.
- The implementation of the Jonglei Canal into the water balance is easier.

In the next figure the division of the area is shown.

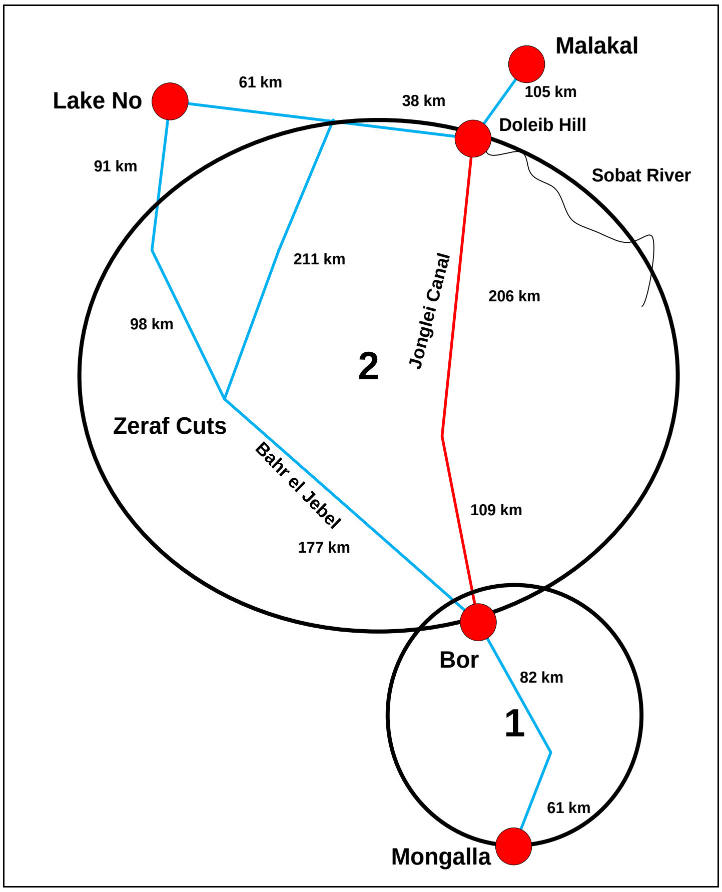

Figure 4 *The Sudd model divided in two areas*

Area 1 will not be affected by the implementation of the Jonglei Canal into the water balance, only area 2, as can be seen in the flow diagram in figure 5.

To complete the water balance for **area 1** the following data is needed:

- The inflow, Q_{in}, at Mongalla
- The outflow, Q_{bor}, at Bor
- The precipitation in the area between Mongalla and Bor
- The evaporation in the Sudd

To complete the water balance for **area 2** the following data is needed:

- The inflow, Q_{bor}, at Bor
- The outflow, Q_{out}, is first calculated by the extraction of the flows at Doleib Hill from the flows at Malakal, to represent the historic water balance, and it is next simulated to depend on the stored water volumes
- The precipitation in the area between Bor and Malakal
- The evaporation in the Sudd.

The evaporation values for both areas are assumed to be the same, because evaporation is highly dependent on temperatures and relative humidity, which are estimate to be almost the same due to their topographical place.

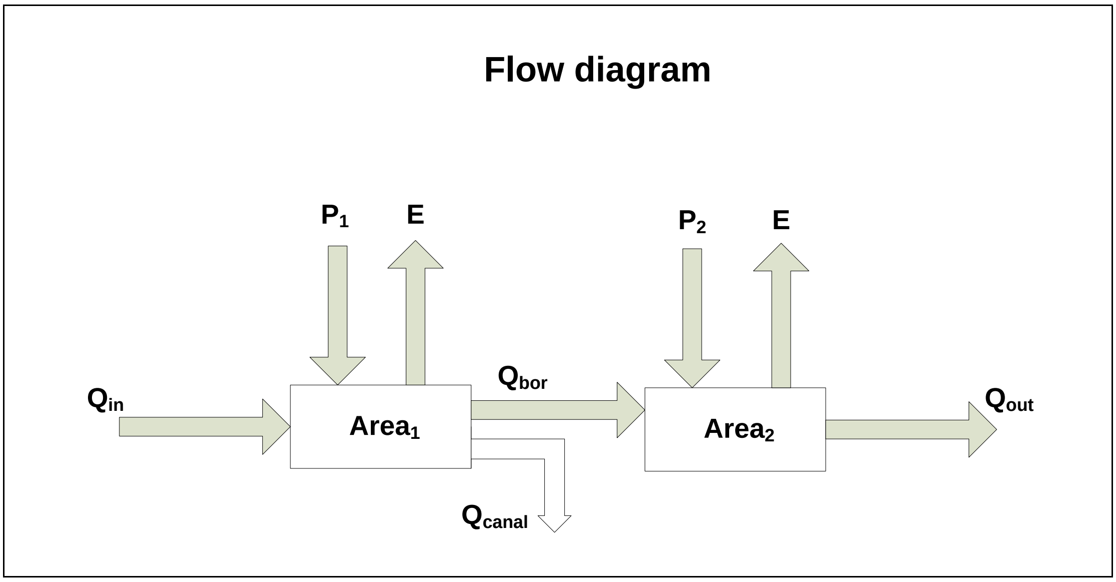

Figure 5 *The flow diagram for the Sudd area, with the two sub-areas*

The volume of precipitation and evaporation that is calculated in the water balance is the amount of precipitation/evaporation multiplied by the corresponding area size of the previous month. The equation will look like:

$$V_{pre,t} = A_{t-1} * P_t$$

$$V_{eva,t} = A_{t-1} * E_t$$

This formula does not take into account that it is possible that the precipitation that takes place outside the existing swamp area will flow to the swamps, and influences the size of the swamps for the next month. The reason is that the Sudd area is relatively flat, so all the water that falls outside the swamp area, will not reach the swamp. Another reason is that all the water that falls outside the area, already has been evaporated before it can reach the swamps (E > P for most months).

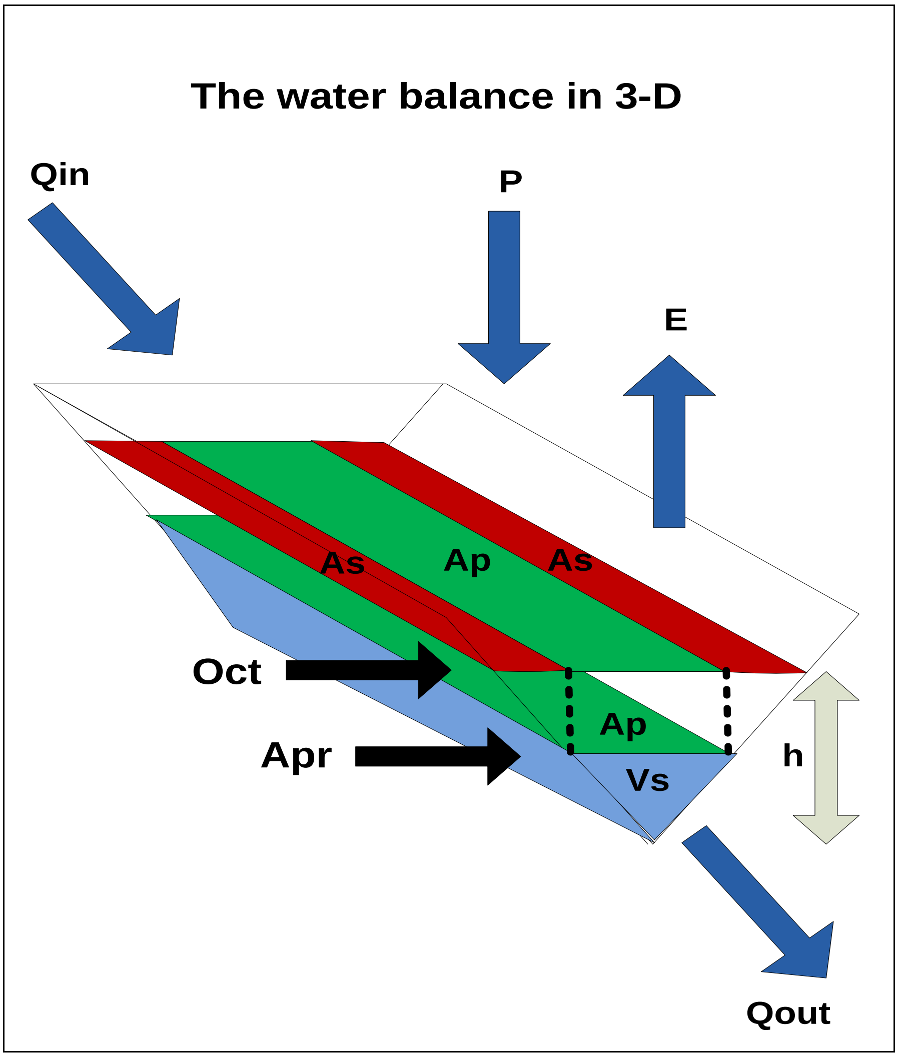

Figure 6 *The simulated swamp types by the water balance*

In figure 6 the different swamp types that will be simulated with the use of the water balance are shown. The permanent swamp (A_p) is the swamp size of the month April, because this is in general the month with the lowest swamp size. The total swamp is the swamp size of the month November, because this is in general the month with the largest swamp size. The seasonal swamp (A_s) is accordingly determined by the difference between the total swamp size and the permanent swamp size:

April (yr_i)	→	**Permanent swamp (A_p)**
October (yr_i)	→	**Total swamp (A_s) + (A_p)**

Seasonal swamp = Total swamp – Permanent swamp

3.3 Adaptation of the hydrological model with Jonglei Canal flows

With the implementation of the Jonglei Canal three variables in the water balance need to be adjusted for the area Bor – Malakal (area 2):

- Inflow; the flow through the canal will be subtracted from the inflow at Bor.
- Outflow; the outflow of the Sudd needs to be recalculated. This will be done by linking the swamps sizes with the simulated outflows. Now new outflows can be calculated based on new swamp sizes.
- Evaporation; the evaporation is highly dependent on the relative humidity of the area. When draining the Sudd, the relative humidity will drop by an estimate of 10 percent in the dry period (October – March)(Mohamed et al., 2005).

With these adjustments for the different variables in the water balance the swamp sizes for different canal flow scenarios can be simulated.

3.4 Implementation of the hydrological model

The simulation of the swamp sizes A, (for both area 1 and 2) will be made using the next equations:

$$A_1 = \left((P_1 - E_1) * A_0\right) + \left(Q_{in,1} - Q_{out,1}\right) + A_0$$

$$A_2 = \left((P_2 - E_2) * A_1\right) + \left(Q_{in,2} - Q_{out,2}\right) + A_1$$

$$A_3 = \cdots$$

A_t = Swamp area (km^2) with t = (1….480) in months
P_t = Precipitation (mm/month)
E_t = Evapotranspiration (mm/month)
$Q_{in,t}$ = Inflow (m^3/month)
$Q_{out,\,t}$ = Inflow (m^3/month)

A_1 = Swamp size (km^2) in January 1961
A_{480} = Swamp size (km^2) in December 2000

The initial starting swamp area A_0 of **area 1 = 1.0 Gm³** and the initial starting swamp area A_0 of **area 2 = 15.0 Gm²** (Sutcliffe & Parks, 1987).

From the initial starting swamp area in January 1961 the monthly swamp size can be simulated until December 2000 with the collected data. The swamp sizes for different canal scenarios can also be simulated by this equation, only with recalculation of some parameters (see paragraph 3.3).

4. Precipitation

4.1 General

The rainfall in the Sudd area varies from an average of 850 mm/yr in the northern part (Malakal) to 1000 mm/yr in the southern part (Mongalla). 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). The ITCZ travels to as far as 20° 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.

4.2 Data

The precipitation data is collected at the Global Precipitation Climatology Centre (DWD/WZN (GPCC), 1996/2005). The GPCC analysis the spatial and temporal distribution of global land-surface precipitation on a monthly time-scale based on in situ observation data. The GPCC data processing steps include quality-control and quality assurance of the station meta data and of the precipitation data, interpolation of the station-related data to regular grids, and the calculation of the spatial means of the 2.5°, 1° and 0.5° latitude/longitude grid box areas.

Figure 7 *The GPCC Visualizer from the Deutsche Wetter Dienst (DWD, 2008)*

The GPCC Visualizer from the DWD creates the opportunity to select user defined areas to collect rainfall data on different grid sizes (0.5°, 1.0° and 2.5°). Another advantage is that the user can select monthly data over a period between 1950 and 2008 which is necessary for this study.

The Sudd will be divided in two parts. The main reason is that there is a substantial difference in the amount of precipitation between the north and south part of the Sudd.

- *Mongalla – Bor*

The area Mongalla – Bor is here defined as:

Longitude	*Latitude*
31.25° – 31.75°	**5.0° – 6.0°**

The dataset that is applied to the area is the GPCC Land surface Full Data Product Version 4 with a grid size of 0.5°.

- Bor – Malakal

The area Mongalla – Bor is here defined as:

Longitude	*Latitude*
30.2° – 31.75°	**6.0° – 9.5°**

The dataset that is applied to the area is the GPCC Land Surface Full Data Product Version 4 with a grid size of 1.0°.

4.3 Output

The results of the analysis of the average yearly precipitation in the Sudd area are given in the following figure.

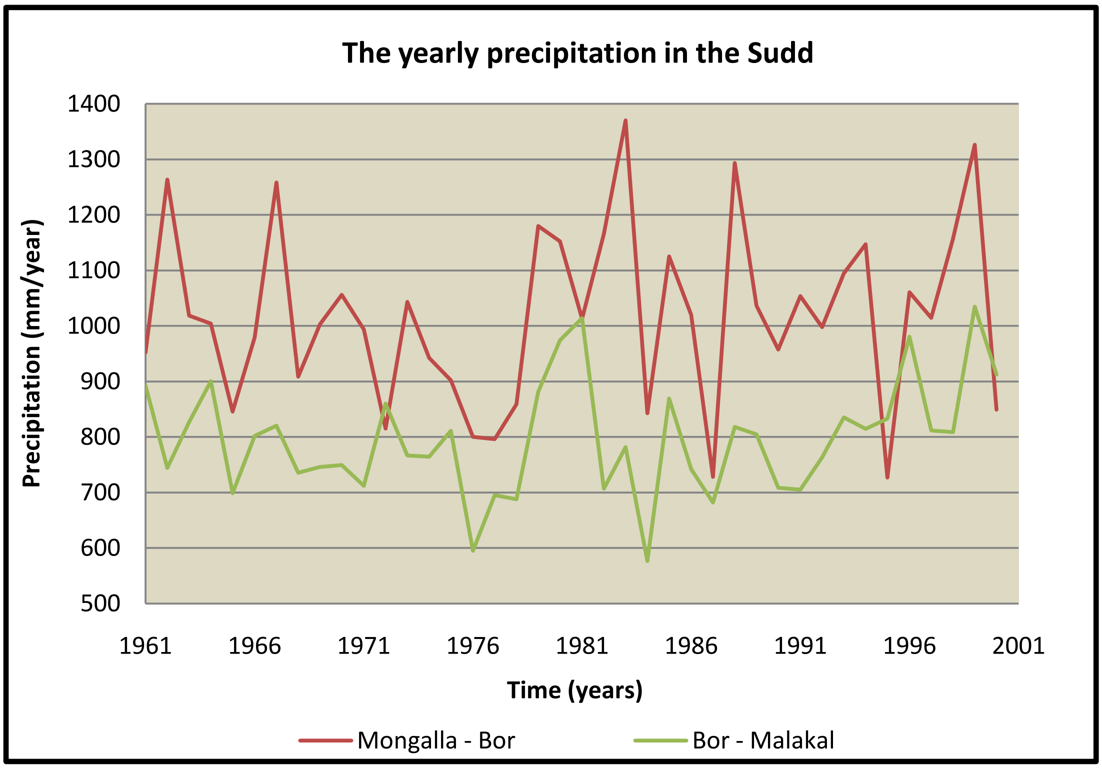

Figure 8 *The yearly precipitation in the Sudd area*

The figure shows no clear pattern of the precipitation for both areas. Both areas have large fluctuation throughout the years. One noticeable detail is that the difference in rainfall between the areas can be very different. While in some years both areas have the same rainfall, in other years the difference can be over 400 mm/year.

Another way to look at the precipitation is to see what months the differences determines the rainfall distribution in the area Mongalla – Bor and Bor – Malakal.

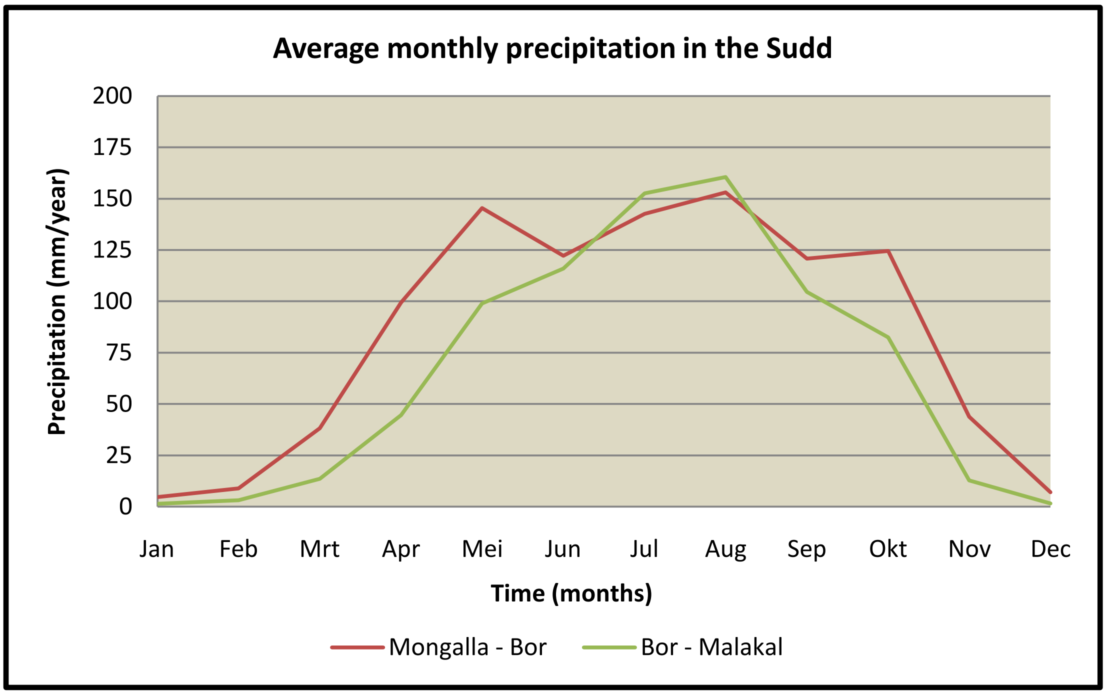

Figure 9 *The average monthly precipitation in the Sudd*

Figure 9 shows that the difference between the two areas can be explained by the fact that particular dry months receive different rainfall amounts. Another remarkable thing is that there is no difference in the rainfall amounts in the two areas in the relative wet months. In this period they have almost the same precipitation.

5. Evapotranspiration

5.1 Evaporation, transpiration and evapotranspiration

Evaporation
Evaporation is the process whereby liquid water is converted to water vapour and removed from the surface. Water evaporates from a variety of surfaces, such as lakes, rivers, and soils.
Energy is required to change the state of the molecules of water from liquid to vapour. Direct solar radiation and the temperature of the air provide this energy. The driving force to remove water vapour from the surface is the difference between the water vapour pressure at the surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.

Transpiration
Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere. Crops predominately lose their water through stomata. These are small openings on the plant leaf through which gases and water vapour pass.
Transpiration, like direct evaporation, depends on the energy supply, vapour pressure gradient and wind. Hence, radiation, air temperature, air humidity and wind terms should be considered when assessing transpiration.

Evapotranspiration
Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET).

5.2 Reference evapotranspiration (ET_0)

The evapotranspiration rate from a reference surface is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics.

The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related.

The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors.

The performance of the various calculation methods reveals the need for formulating a standard method for the computation of ET_o. The FAO Penman-Monteith method is recommended as the sole standard method. It is a method with strong likelihood of correctly predicting ET_o in a wide range of locations and climates and has provision for application in data-short situations.

5.3 FAO Penman-Monteith equation

The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The requirements that the grass surface should be extensive and uniform result from the assumption that all fluxes are one-dimensional upwards.
The FAO Penman-Monteith method is selected as the method by which the evapotranspiration of this reference surface (ET_o) can be determined, and as the method which provides consistent ET_o values in all regions and climates.

A panel of experts (International Commission for Irrigation and Drainage and the World Meteorologic Organization) recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration and advised on procedures for calculation of the various parameters (FAO, 1998). By defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23 (see figure 10), closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, the FAO Penman-Monteith method was developed. The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data worldwide.
From the original Penman-Monteith equation and the equations of the aerodynamic and surface resistance, the FAO Penman-Monteith method to estimate ET_o can be derived:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{(FAO, 1998)}$$

where,

ET_o = reference evapotranspiration [mm day^{-1}]
R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}]
G = soil heat flux density [MJ m^{-2} day^{-1}]
T = mean daily air temperature t 2 m height [°C]
u_2 = wind speed at 2 m height [m s^{-1}]
e_s = saturation vapour pressure [kPa]
e_a = actual vapour pressure [kPa]
e_s - e_a = saturation vapour pressure deficit [kPa]
D = slope vapour pressure curve [kPa °C^{-1}]
g = psychometric constant [kPa °C^{-1}]

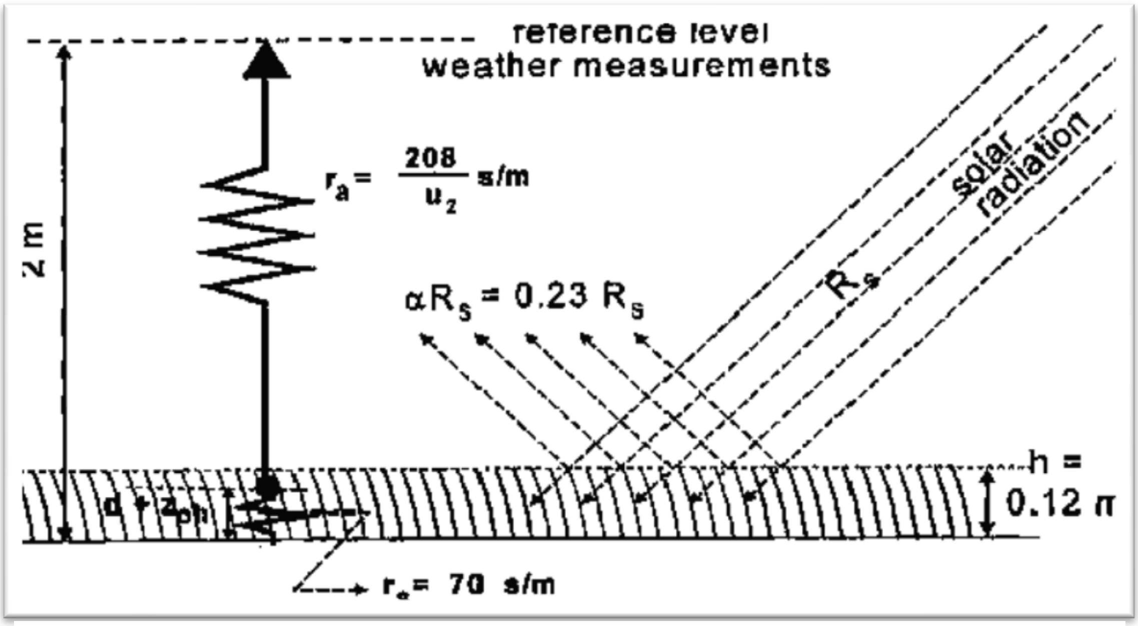

Figure 10 *Characteristics of the hypothetical reference crop (FAO, 1998)*

The equation uses standard climatologically records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water.

5.4 Calculation of ET_0

The calculation of the ET_0 is further explained in appendix A.

5.5 From reference evapotranspiration to actual evapotranspiration

The actual evaporation E_a is expected to be substantially lower than the reference evaporation E_o as the basin does not exist of a reference crop (12 cm clipped grass) with ideal moisture regimes throughout the whole year.

The actual evaporation can be calculated when dealing with the seasonal variation of evaporation through the variation of the relative evaporation ratio E_a/E_o, which in the irrigation literature is known as the crop coefficient K_c.

The expression to calculate the monthly actual evaporation E_a:

$$E_a = E_0 * K_c$$

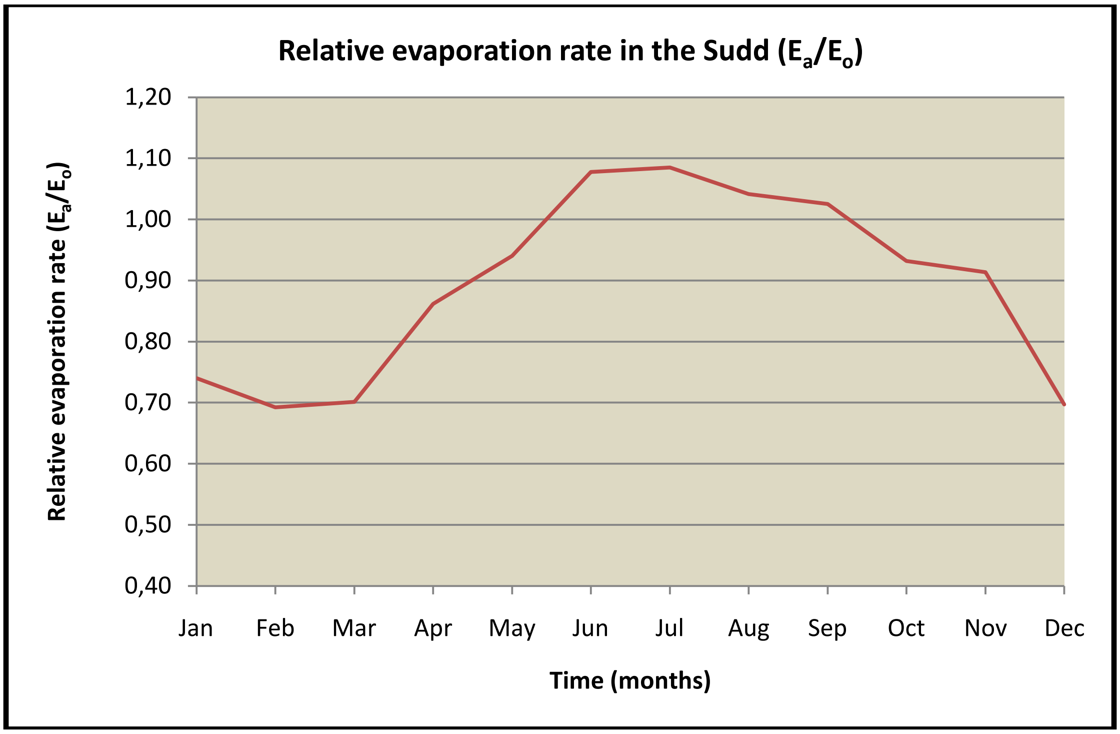

Figure 11 *The average crop factor K_c for the Sudd during three years (1995, 1999 and 2000)*

The fraction E_a/E_0 is determined as an average over three years (1995, 1999, 2000). These three years were used, because these years the actual evapotranspiration was calculated using SEBAL techniques (Mohamed, 2005). With the output from the ET_0 calculator the crop factor K_c has been calculated (Figure 11).

A maximum value of $E_a/E_o = 1.10$ occurs in the Sudd in the middle of the wet season, which shows that papyrus and other types of rough vegetation have an evaporation rate more than standard clipped grass considered in the definition of E_0 (Howell et al, 1988)

5.6 Results

In the next figure the average yearly actual evapotranspiration is shown for the period 1961 – 2001.

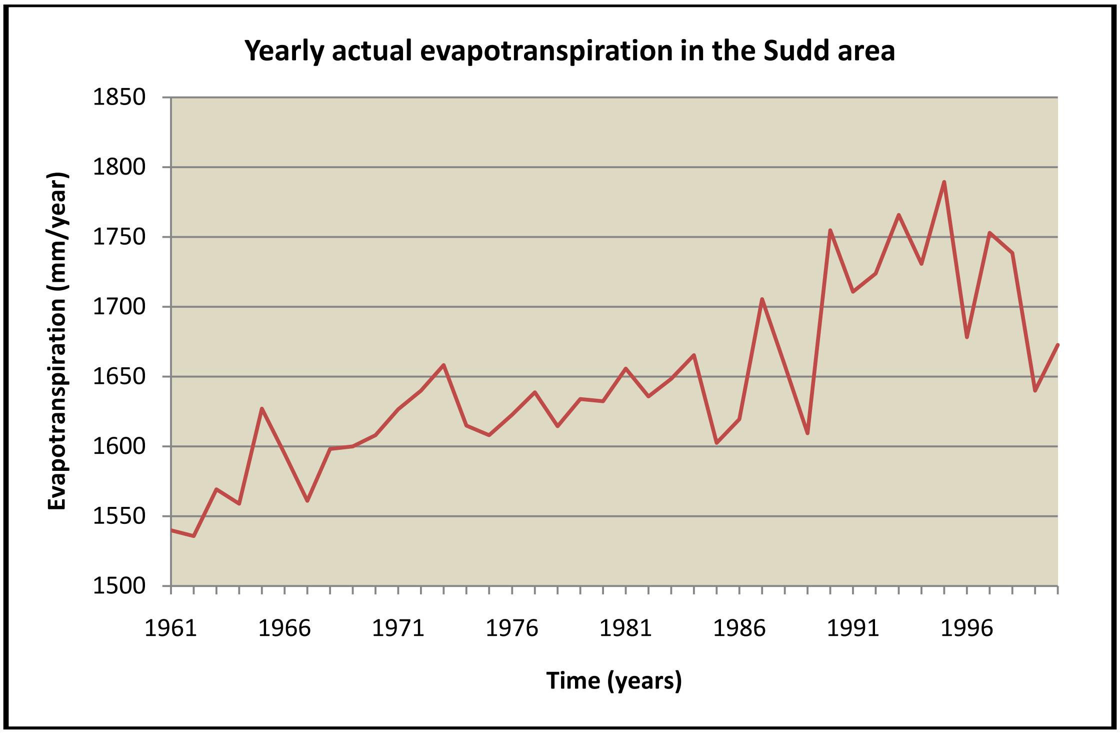

Figure 12 *The yearly total actual evapotranspiration in the Sudd area*

The actual evaporation shows an average increase from 1961 until 1995, with some years that have low evaporation rates (eg. 1989). This increase is mainly caused by a decrease in the solar radiation and relative humidity (see Appendix A, figures 32 and 33). After 1995 the evaporation rate is decreased, caused by an increase in the solar radiation/relative humidity in the Sudd area.

6. Inflow

6.1 General

Mongalla, a town situated at the upper reach of the Bahr el Jebel is the key gauging station for inflows into the Sudd swamps of southern Sudan. Due to political circumstances, flow measurements have been stopped in 1983, leaving the inflow into the swamps ungauged. It resumes in 2007 after the peace agreement of 2005. The flows at Mongalla are a combination of Lake Victoria discharge, influenced by evaporation, damping and storage effects of the Equatorial Lakes (Albert, Edward, Kyoga) and seasonal torrent runoff during the rainy season. Historically, the importance of the torrent flows for processes in the Sudd swamps, like their influence on the flood extent and yearly variations, was reported by Hurst and Phillips (1938). They described the Equatorial Lakes discharges as not varying significantly over the seasons in normal years and having a fair correlation between flows of successive years. The torrents on the other hand are highly seasonal and depend on the local rainfall pattern, with the flow in successive years depending solely on the rainfall and not showing any serial relation despite to the general rainfall pattern which fluctuates over the years. This general picture highlights the importance of the torrential flows for the total discharges at Mongalla.

Bor, the location where the flow from the Bahr el Jebel will be diverted into the Jonglei Canal, is also considered to be an inflow location for this study as described in the previous chapters. From Mongalla to Bor, over a distance of 140 km, some flow will be lost due the ratio evaporation/precipitation. According to Sutcliffe and Parks (1987) this can be estimated at two percent. The flows at Bor will only be related to the inflows at Mongalla.

Figure 13 *The inflow of the Sudd*

6.2 Data

Mongalla

The flow series of the White Nile at Mongalla covers the period 1905-1983 which are available from the Nile Control Staff (2000, 2007). The flows at Mongalla are equal to the flows at Pakwach (Lake Albert outflow) plus the inflow by the torrents between Pakwach and Mongalla. The completion of the series of Mongalla for the period 1984 – 2000 and the torrents have been carried out as follows (RIBASIM, 2008)

- For the periods 1984-1992 and 1996 a 4 step approach has been used:
    - Annual flows at Mongalla have been derived from regression on Pakwach (excluding the years 1916, 1917 and 1964):
      $Q_{mongalla} = 4.655 + 0.941 Q_{pakwach} + \in$
      where $\in$ (a,b)= is a normal deviate with mean a = 0 and standard deviation $b = 0.12$.
    - Annual torrent flows have been calculated for above years as the difference between Mongalla and Pakwach;
    - Monthly torrent flows have been estimated from the annual torrent flows by scaling according to the average monthly percentage of the annual flow;
    - Monthly flow values for Mongalla have been derived from the monthly flows at Pakwach and of the torrents.

For the periods 1993 - 1995 and 1997 - 2000 10-day mean gauge heights of Juba have been used to estimate the gauge height at Mongalla.

Bor

The discharge at Bor will be totally dependent on the flows at Mongalla. The flows at Mongalla will be multiplied by a factor of 0.98 to calculate to flows at Bor (Sutcliffe & Parks, 1987).

6.3 Output

Figure 14 shows the average monthly flows for three locations. The flows at Mongalla and Bor are described above, while the outflow at Lake Albert is included to show the torrential influence between Lake Albert and Mongalla.
During the dry months, the three flows are almost equal. At the start of the rainy season in April the flows at Mongalla and Bor increase substantially due to the torrents between the outflow at Lake Albert and Mongalla. The outflow at Lake Albert shows almost no fluctuation during the year, because the flow is highly controlled by the outlet location Jinja of Lake Victoria.

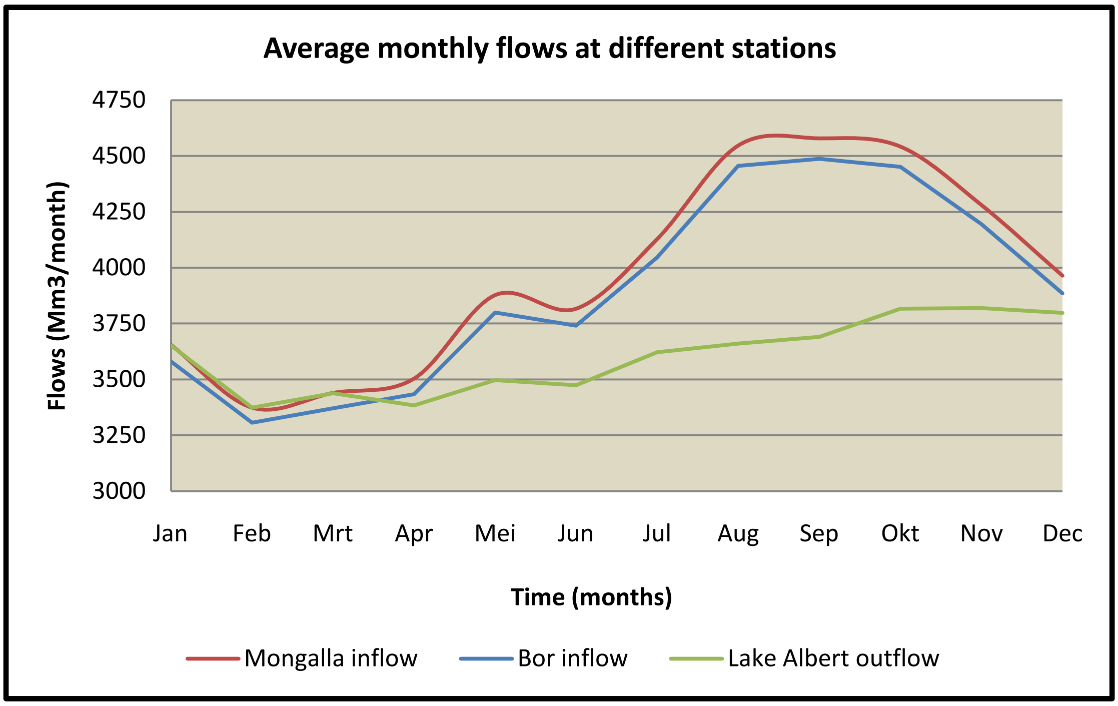

Figure 14 *The average monthly flows at Mongalla, Bor and Lake Albert (RIBASIM, 2008)*

Figure 15 shows the average yearly flows for these locations. The difference between the flows at Mongalla and Bor is only 2 percent as explained. The result is that the line for Mongalla and Bor are almost similar. The outflow at Lake Albert is close to the inflows at Mongalla and Bor when there is a relatively dry year and vice versa. When the flows at Mongalla and the outflow at Lake Albert show a large difference this should be caused by the high rainfall amount and the resulting high flows from the torrents. The instantly increase during the early 60s is mainly caused by the increase rainfall over Lake Victoria, resulting in very high outflows. The overall picture is that the average flows of the three stations decreased dramatically during the period 1961 – 2001, with some peak flows in some years. The inflow peak in 1964 was 65.000 m^3/s, while the flow in 2001 only reached to 40.000 m^3/s, a decrease by 25.000 m^3/s.

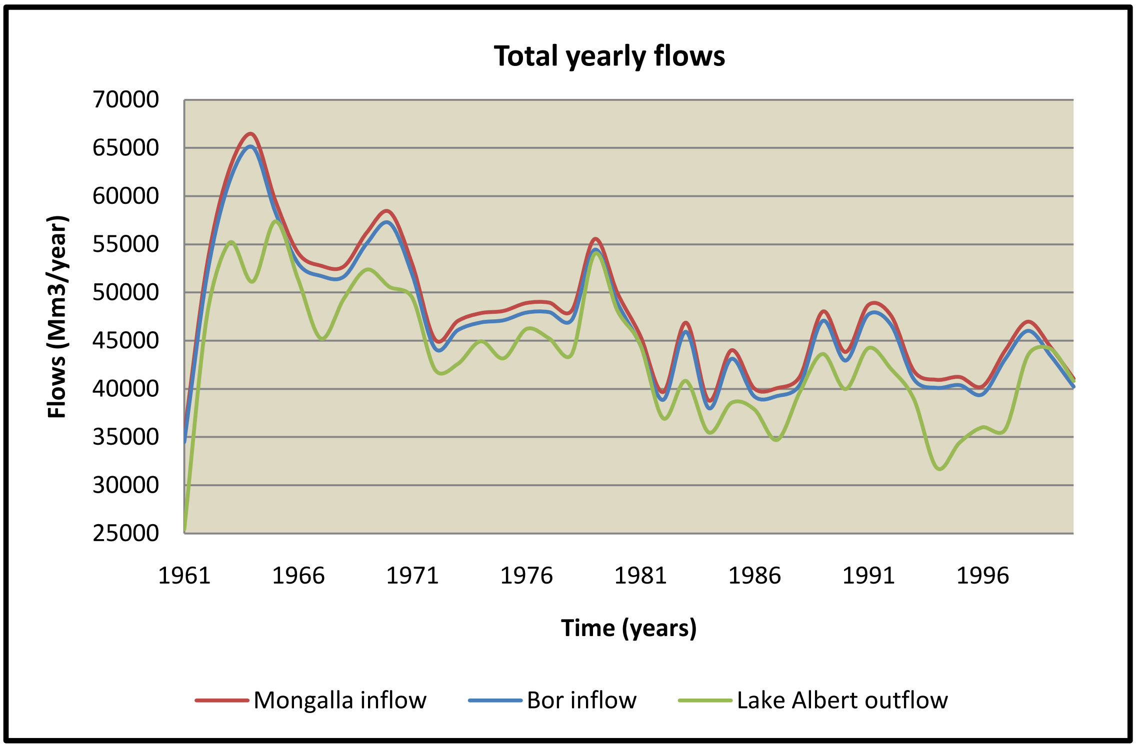

Figure 15 *The total yearly flows (RIBASIM, 2008)*

7. Outflow

7.1 General

The outflow from the Sudd is in most studies (Mohamed, 2005; Sutcliffe and Parks, 1987) described as the difference between the flows of the White Nile at Malakal and the Sobat at Doleib Hill near its mouth. In this study the same approach for the outflow will be used. In order to simulate the outflows from the Sudd, the flows at Doleib Hill and Malakal are needed.

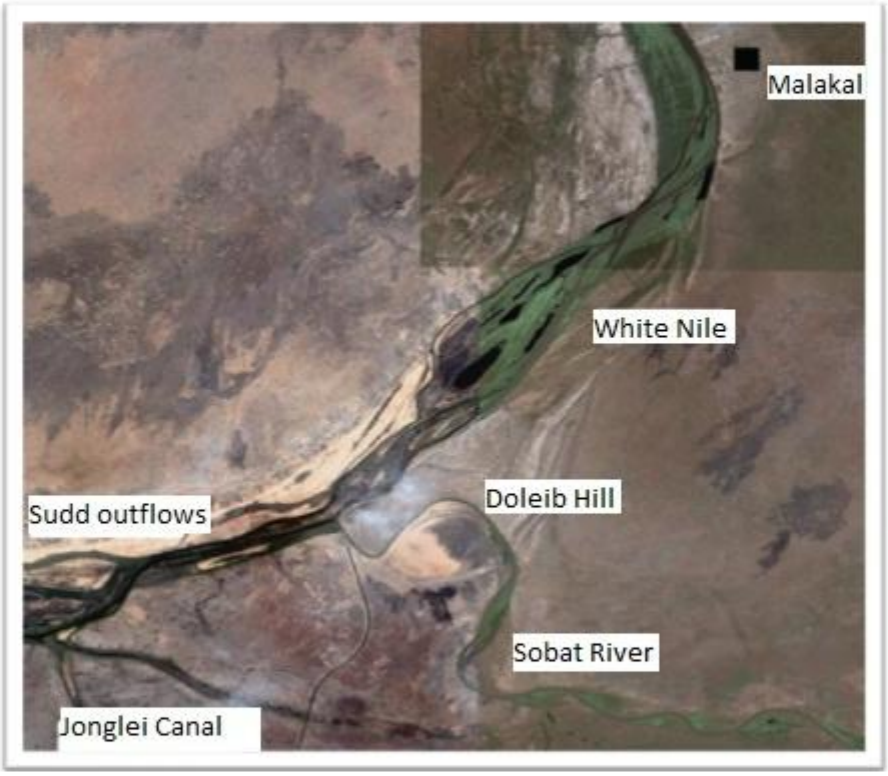

Figure 16 *The outflow of the Sudd*

7.2 Data

Doleib Hill

The monthly flow record of the measurement station Doleib Hill at the mouth of the Sobat River as published by the Nile Control Staff covers the period 1905 -1983. After 1983 there are no records published from the station. There will need to be a simulation to collect this data.

Malakal

The monthly flow record for the White Nile at Malakal as published by the Nile Control Staff covers the period 1906-2002. The monthly record has subsequently been obtained as the average monthly percentage of the annual flow.

Extrapolation of the Doleib Hill flow records to the period 1983 - 2000

The extrapolation of the flow records will be based on the monthly relation between the flows at Malakal and the flows at Doleib Hill for the period 1961 – 1983.

This resulted in twelve equations that describe the relation between the flows at Doleib Hill and Malakal for every month (see table 2):

Month	Relation Doleib Hill (Q_{db})/Malakal (Q_m) (in Mm³/month)	R^2
January	$Q_{db} = -0.0001*Q^2_m + 1.47*Q_m - 2134$	0.57
February	$Q_{db} = -0.0002*Q^2_m + 1.59*Q_m - 1851$	0.53
March	$Q_{db} = -0.0003*Q^2_m + 1.56*Q_m - 1714$	0.30
April	$Q_{db} = -0.00005*Q^2_m + 0.02*Q_m + 130$	0.08
May	$Q_{db} = -0.0001*Q^2_m + 0.69*Q_m - 497$	0.13
June	$Q_{db} = -0.0003*Q^2_m + 1.64*Q_m - 1216$	0.06
July	$Q_{db} = -0.0002*Q^2_m + 0.99*Q_m - 102$	0.01
August	$Q_{db} = 0.00006*Q^2_m - 0.03*Q_m - 2052$	0.04
September	$Q_{db} = -0.00004*Q^2_m + 0.42*Q_m + 763$	0.17
October	$Q_{db} = -0.00003*Q^2_m + 0.46*Q_m + 671$	0.28
November	$Q_{db} = -0.0001*Q^2_m + 1.46*Q_m - 1697$	0.44
December	$Q_{db} = -0.0002*Q^2_m + 2.12*Q_m - 3475$	0.68

Table 2 *The regression equations for different months between the flows at Doleib Hill and Malakal with the corresponding* R^2

With the known monthly flow records at Malakal for the period 1984 – 2000, the flows at Doleib Hill for the same period can be simulated.

In the next figure, the flows at Doleib Hill are compared with the flows simulated by the RIBASIM model (2008). The RIBASIM model has simulated a 103-year natural monthly flow series (1900 – 2002) for several stations for the Nile upstream of Lake Nasser, including Doleib Hill. Data from the Nile Control Staff have been combined with results from hydrological studies to simulated these data sets.

The RIBASIM model uses the next regression to simulate the flows at Doleib Hill:

$$Q_{db} = Q_m - Q_{out} \qquad \text{(Mm}^3\text{/month)}$$

$$Q_{out} = 6.574 - 0.29Q_m \qquad \text{(Mm}^3\text{/month)}$$

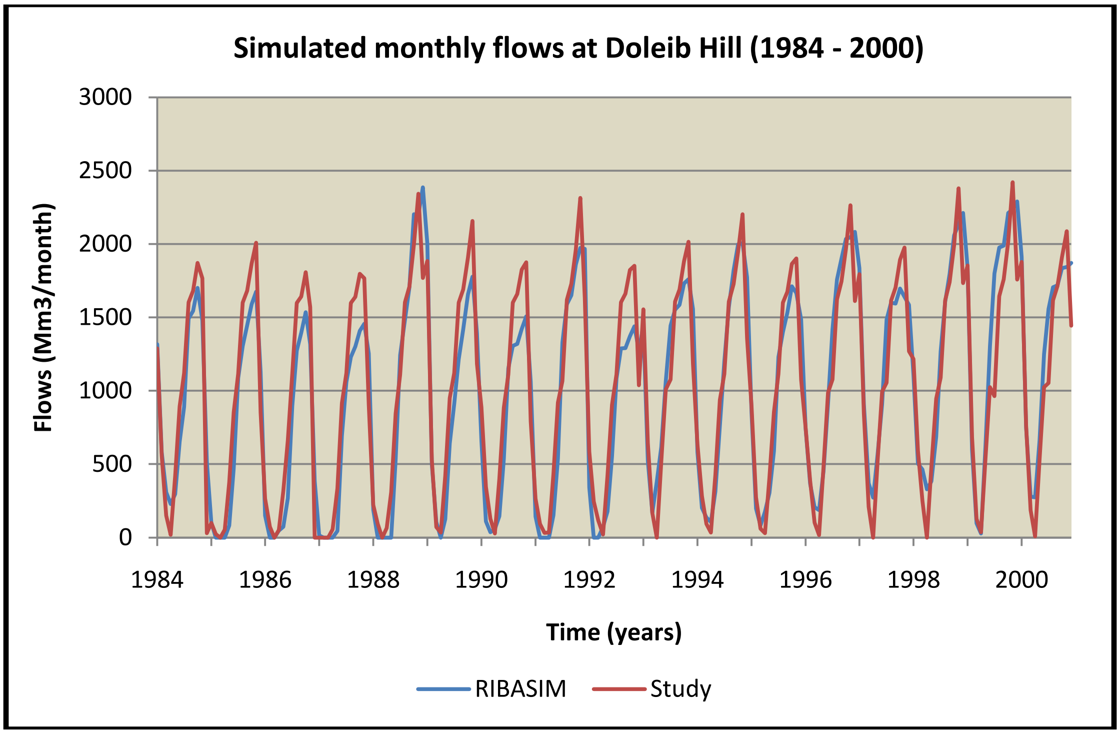

Figure 17 *The simulated monthly flows at Doleib Hill*

The results in figure 17 show the high similarities between the simulations from the RIBASIM model as from this study. Although the monthly regression equations in this study show low values for R^2, the results are quite good compared with the regression equation used in the RIBASIM model.

All remaining monthly flows at Doleib Hill and Malakal for the period 1984 – 2000 are simulated. As a result the monthly Sudd outflows can be calculated for the total period 1961 - 2000.

7.3 Output

Figure 18 shows the flows at Malakal, Doleib Hill and the outflow of the Sudd. After the peak in the early 1960s, the outflow and the other flows have become relatively stable. The outflow of the Sudd fluctuates around 18.000 Mm^3/year for the period 1971 – 2000. The flow at Malakal is decreasing from his peak flow around 1965 until the end of the 1980s. After that period there have been some increasing flows until 2000. The flows at Doleib Hill show more or less the same trend, with a negative highlight in 1982.

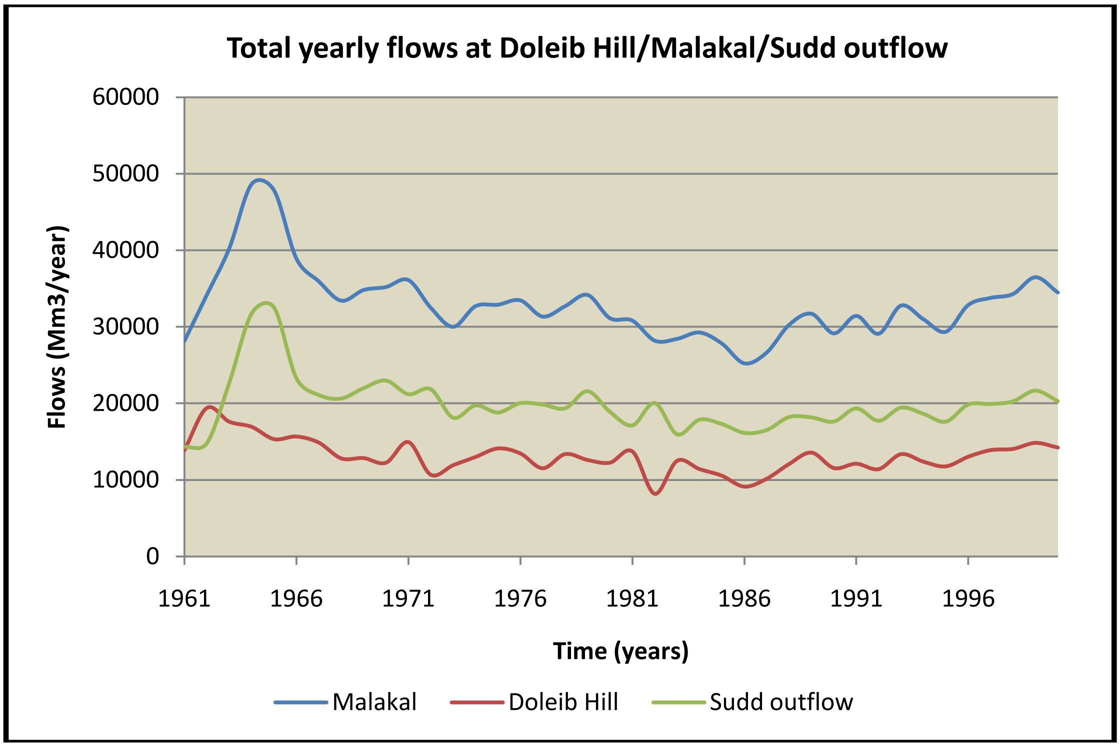

Figure 188 *Total yearly flows at Doleib Hill/Malakal/Sudd outflow*

The average monthly discharge in figure 19 shows the very stable outflow during the year. The flows at Malakal and Doleib Hill are in contrary, seasonally dependant. The outflow circulates between 1500 and 2000 m^3/month, while the flows at Malakal and Doleib Hill have a very large range during the year. The flow at Malakal has a range from 1800 Mm^3/month – 3750 Mm^3/month and the flow at Doleib from almost 0 till 2000 Mm^3/month in November.

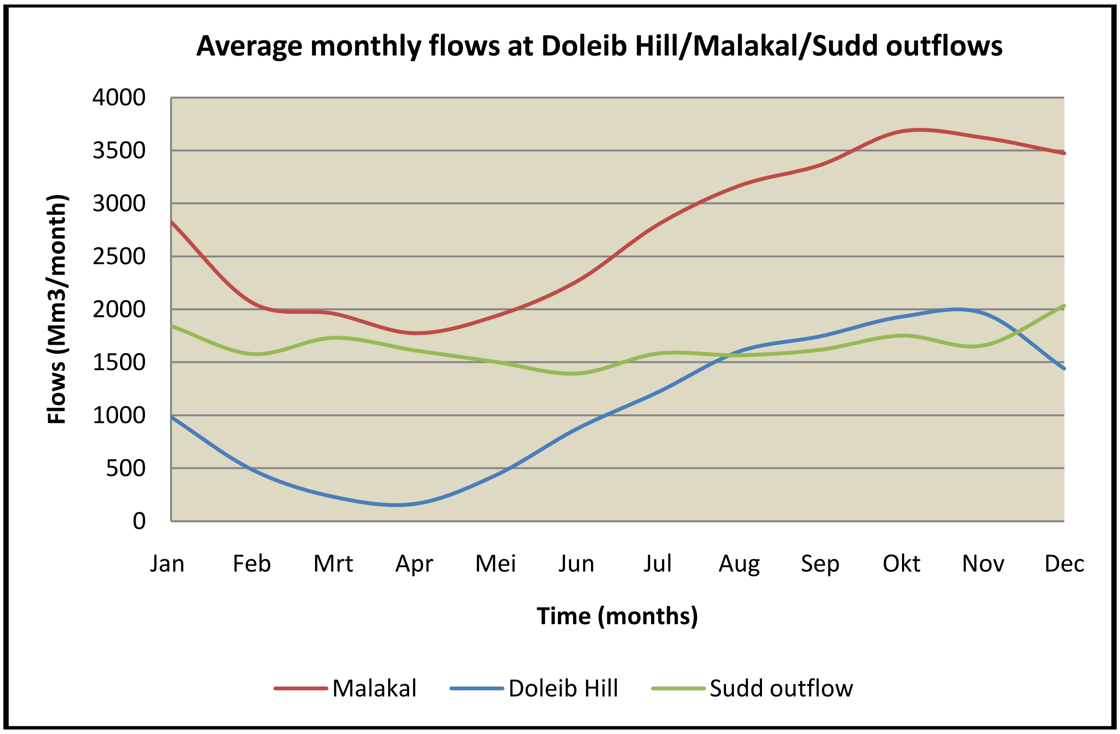

Figure 19 *The average monthly flows at Doleib Hill/Malakal/Sudd outflows*

8. The water balance

8.1 Simulation of the historic Sudd water balance

Starting from an initial storage volume of 1.0 Gm³ on 1 January 1961 for the area between Mongalla and Bor (area 1) and 15 Gm³ for the area between Bor and Malakal (area 2), the flooded area was simulated for monthly intervals until December 2000. The results of the total simulated swamp sizes (area 1 + area 2) are plotted in figure 20.

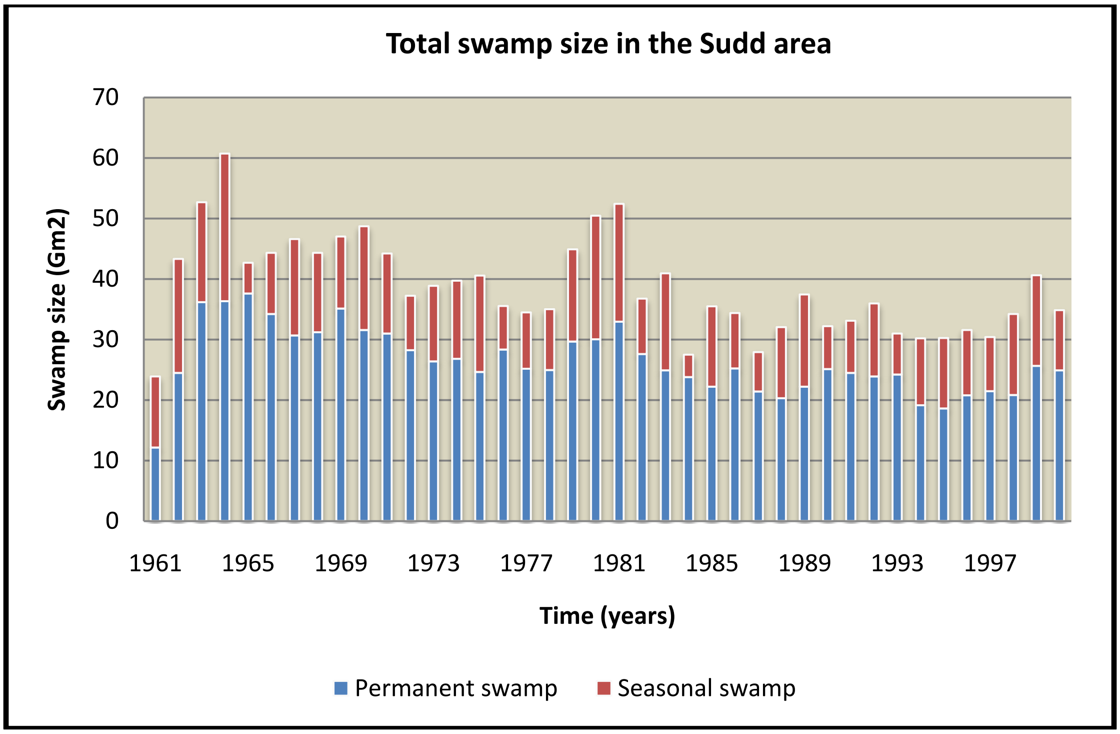

Figure 19 *The total swamp size of the Sudd area*

Figure 20 shows the fluctuation of the swamp size over the period 1961 – 2001. The early 1960s have a big increase in the total swamp size, caused by the high rainfall on Lake Victoria, resulting in a high inflow at Mongalla. After 1965 the total swamp size fluctuates from 35 Gm² to around 45 Gm² in the period until 1980. After 1980 there are three years where the total swamp size shows a big decrease. In 1984 the swamp size recovers itself to around 35 Gm². In the rest of the period the total swamp size is around 30 Gm².

The change in the swamp size is mainly caused by four variables: the inflow, outflow, precipitation and the evaporation. One of these variables has more influence on the change in swamp size than the other variable, but what weight have the different variables on the change in the swamp size?

The weights will be determined as follow:

Variable	Weight (absolute)	Weight (%)
Inflow	m^3/month (1)	(1) / (5) * 100 %
Outflow	m^3/month (2)	(2) / (5) * 100 %
Precipitation	mm/month * A_t (3)	(3) / (5) * 100 %
Evapotranspiration	mm/month * A_t (4)	(4) / (5) * 100 %
Total	∑ 1 + 2 + 3 + 4 (5)	100 %

Table 3 *The weight for every variable on the change of the swamp size*

The results are displayed in figure 21 and table 4.

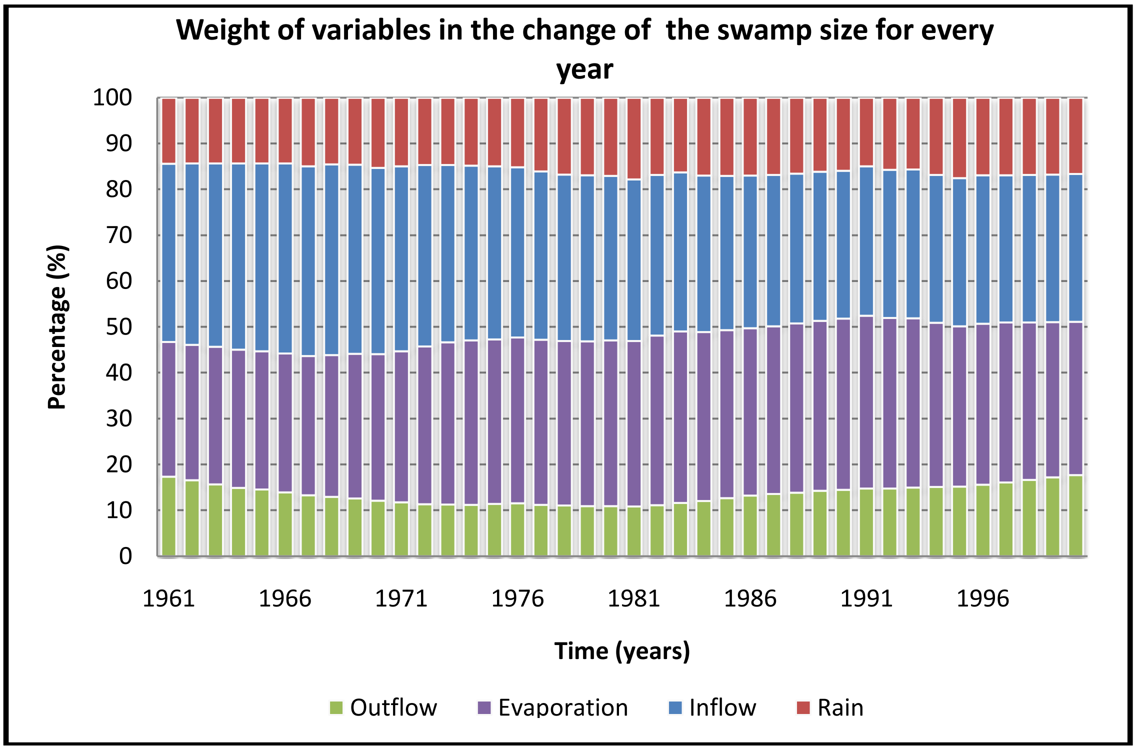

Figure 21 *The weight of variables in the change of the swamp size for every year*

Parameter	Weight (%)
Inflow	36.1
Outflow	13.6
Precipitation	15.8
Evapotranspiration	34.5

Table 4 *The average weight of a parameter on the change of the swamp size*

From figure 21 and table 4 can be concluded that the inflow and evaporation are the two variables that have the most impact on the change of the swamp size. The inflow and evapotranspiration are almost three times more important than the outflow and precipitation.

8.2 Verification of the Sudd water balance

The verification of the water balance will be made by comparing satellite images taken by the Landsat satellite with the calculated swamp sizes from the water balance.

The satellite images of the Sudd area can be found of the website of the USGS (United States Geological Survey). With the USGS Global Visualization Viewer it is possible to download images to determine the swamp size for a specific date.

An example of an image (190 km x 190 km) is one from December 1990 (see figure 22). The figure shows only 1/3rd of the total Sudd area. The determination of the swamp size can only be done by using three images that cover the whole area. A raster will be set over the image to count the amount of cells that cover swamp parts. The green colors in the figure show the swamp, while the pink color shows the non-swamps parts. Although it is hard to really measure accurate the size of the swamp (some parts are lighter green, some are darker green) from these satellite images, it gives an estimate of the swamp size of that specific date.

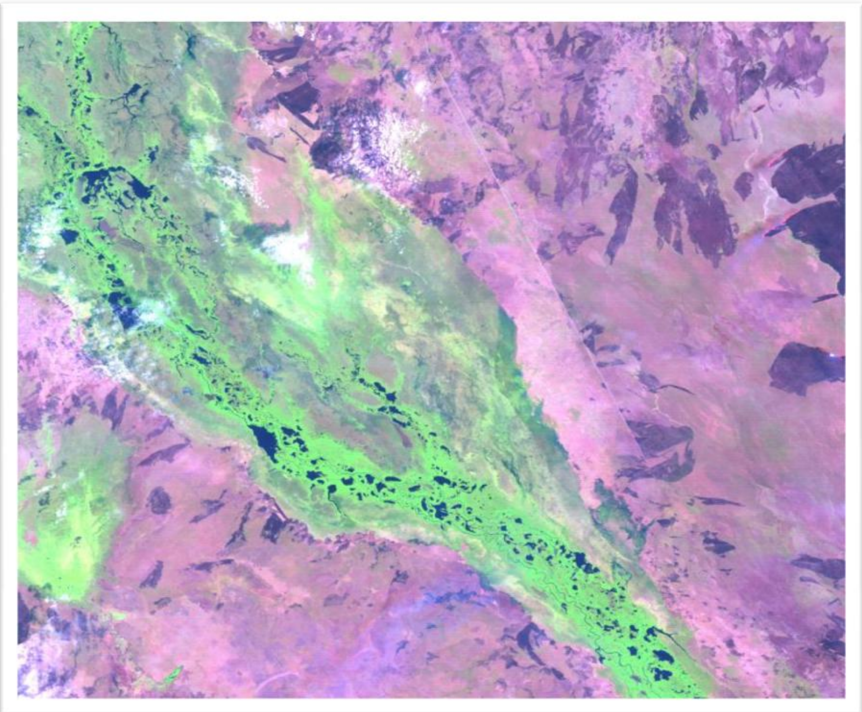

Figure 22 *The satellite image of a part of the Sudd swamp in December 1990*

Table 5 shows the results.

Date	Simulated swamp storage	Satellite assessment
Feb-73	27.3 Gm^3	23.5 Gm^3
Dec-79	39.4 Gm^3	40.4 Gm^3
Dec-84	22.6 Gm^3	19.5 Gm^3
Dec-86	26.7 Gm^3	23.8 Gm^3
Dec-90	26.5 Gm^3	24.4 Gm^3

Table 5 *Measured swamp sizes by satellite assessment compared with simulated swamp sizes*

From the results of table 5, it can be concluded that the swamp sizes calculated by the water balance, are almost equal to the measured swamp sizes by the satellite images. The used data for the different variables is qualified to simulate swamp sizes for the Sudd area.

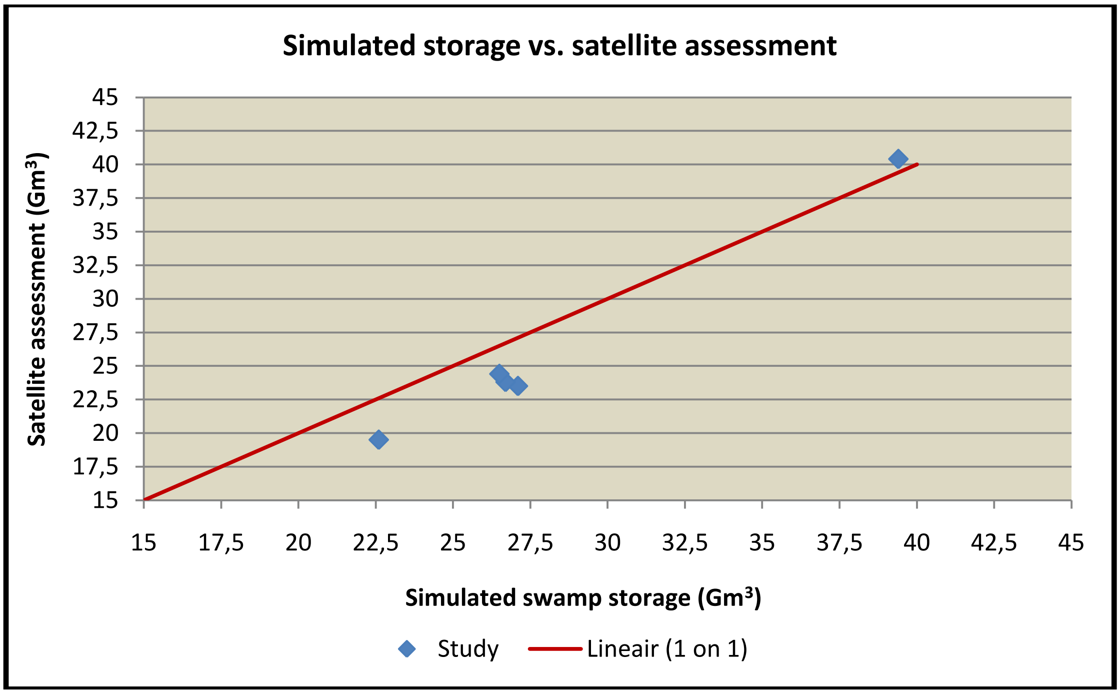

Figure 23 *The simulated storage vs. satellite assessment*

The above figure shows the relation between the simulated storage versus the satellite assessment. The black dots show the data that is represented in table 5. As can be seen, there is almost a 1:1 relation between the simulated storage and the satellite assessment. The conclusion can be made that the simulated swamp size closely represents the actual measured swamp size.

8.3 Conclusions on the simulation of the historic water balance

The simulation of the swamp sizes for the period 1961 – 2000 have been carried out using the described hydrological model. They show good results compared with measured swamp size by satellite data using Landsat images.

The simulations of the historic water balance of the Sudd show some characteristic results for certain periods. These periods can be divided into four groups:

1. **1961 – 1964** The increase of the total swamp size by almost 300 % from an initial 15.0 Gm^3 to a maximum of over 60 Gm^3. The effects on the seasonal and permanent are quite similar for that period.
2. **1965 – 1978** After the high decrease of the total swamp size from 62 Gm^3 to 42 Gm^3 (1964 – 1965), the total swamp size continued to decrease, although relatively slow. The total swamp size in 1978 was around 35 Gm^3. The relation between the permanent and seasonal changed compared with the previous period. While the relation between the permanent/seasonal swamp in the period 1961 – 1964 around 50/50 was, the relation in the period 1965 – 1978 was changed 75/25.
3. **1979 – 1981** After 1978 there was a high decrease of the total swamp until 1981, from 35 Gm^3 to 52 Gm^3. In that period the relation between the permanent/seasonal swamps changed again. This time the seasonal swamp recovered itself to a relation around 65/35. The main cause for the increased swamp size would be the higher rainfall in the area during that period (see figure 8, Bor – Malakal).
4. **1982 – 2000** After 1981 the total swamp size is relatively stable, fluctuating around 30 Gm^3. The relation between the permanent/seasonal swamps has changed for the third time. This time the seasonal swamp is even smaller, which result in a relation of around 72/25.

The verification of the simulated swamp size with the measured swamp size shows a difference in swamp size with a maximum of 10 percent. The conclusion is that the simulation of the historic Sudd water balance has been successful by the hydrological model used in this study. As well can be concluded that the used data sets for the four variables in the model (inflow, outflow, evaporation and precipitation) are quite good simulated.

9. The operation of the Jonglei canal

9.1 General

The Jonglei Canal project, considered one of the most important cooperation projects between Egypt and Sudan, was halted in 1983 as a result of the Sudanese civil war. The primary objective of the project was to ensure the flow of 4.8 billion cubic meters of water annually, to be equally distributed between Egypt and Sudan, and provide a model for similar water-conservation initiatives in other areas, such as the Mashar swamps and the swamps of the Bahr al-Ghazal area. The first stage of the project included the digging of a canal to provide approximately 2.4 billion cubic meters of water annually. A second canal was to double this amount, subject to agreement with the countries of the equatorial lakes.

9.2 The effects

The Jonglei Canal was designed to bypass the Sudd and direct downstream a proportion of the water that is 'lost' from the Nile each year by spill and evaporation in the swamps.

The canal has not been completed, but detailed surveys were undertaken to determine a whole range of effects, many of which will be shown to be disadvantageous to the inhabitants of the Jonglei Area. Some of the effects are described below (Howell et al, 1988):

- The river-flooded grasslands are an essential seasonal resource during the driest months of the year. Not only is there drinking water available in the rivers, but the process of seasonal inundation itself produces species of grasses which sustain the herds from about January until April. It follows that the river-flooded grasslands are crucial to the pastoral economy at this time of the year. It is, however, just these grasslands that may be reduced by the operation of the canal.

- The water benefit of the canal downstream will be around 4 Gm^3/yr and according to some estimates even an extra water flow of up to 10 Gm^3/yr may be reached. These quantities are a substantial percentage of the average 'losses' by the evapotranspiration, the natural production of river-flooded grasses being a function of the annual fluctuation in river discharge and thus of the annual variation in area flooded.

- The established fisheries of some large lakes in the Sudd are said to have been adversely affected by increased water depth, but, overall, the flooding of the 1960s has multiplied the number of perennial lakes in the system and, thereby, the fishing potential. A severe decrease in the discharge into the Sudd resulting from the Jonglei canal would bring about the total disappearance of many lakes in the papyrus zone and reduce others to the status of seasonal lagoons, with a serious loss of year-round fish and fishing potential.

- The canal will in many areas drive a barrier between wet season villages and dry season grazing grounds along the river channels and therefore dislocate the pastoral cycle. Many people living east of the canal will have to cross it with their livestock when regrowth from rain-flooded grasslands is exhausted and they have to move westwards to the river-flooded grasslands of the Nile.

There exists a kind of 'Jonglei Controversy'. The criticism of the environmentalists are many but can be placed into charges that the Jonglei Canal will drastically affect climate, groundwater recharges, silt and water quality, the destruction of fish and changes in the lifestyle of the people. However, other studies claim that the positive effects will counterbalance by far the negative effects.

9.3 Operation rules of the Jonglei Canal

As described above, the implementation of the Jonglei Canal will result in several effects. To study these effects, several alternative operating rules will be examined. The operating rules will be split into three parts:

- Fixed canal flows
- Seasonal dependent canal flows
- Extra water volume downstream

A fixed discharge during the year gives an insight on the effects on the swamp sizes on the long term. Seasonal dependent canal flows will give actors of 'nature' the opportunity to either maintain particularly the permanent or the seasonal swamp, or protect the stakes of actors depending on these areas by regulating the flows during the wet and dry period. The last set of scenarios will be tested, because as planned there will be needed an extra volume of 4.8 Gm^3 downstream of the Sudd.

9.4 Adjustments in the hydrological model

As described in paragraph 3.3, the hydrological model needs to be adjusted to calculate the new swamp sizes. Three variables need to be recalculated:

- **Inflow**
  The flows through the Jonglei Canal need to be extracted from the flows at Bor to create the new inflow:

  $Q_{in,new} = Q_{bor} - Q_{canal}$

- **Outflow**
  The outflow of the Sudd will change as a result of the changing swamp size. To simulate the outflow in this new situation, a relation will be made with the monthly swamp size and the Sudd outflow. There will be made a monthly relation, because of the seasonal cycle of the swamps. This will result in the following monthly relation between swamp size and Sudd outflow.

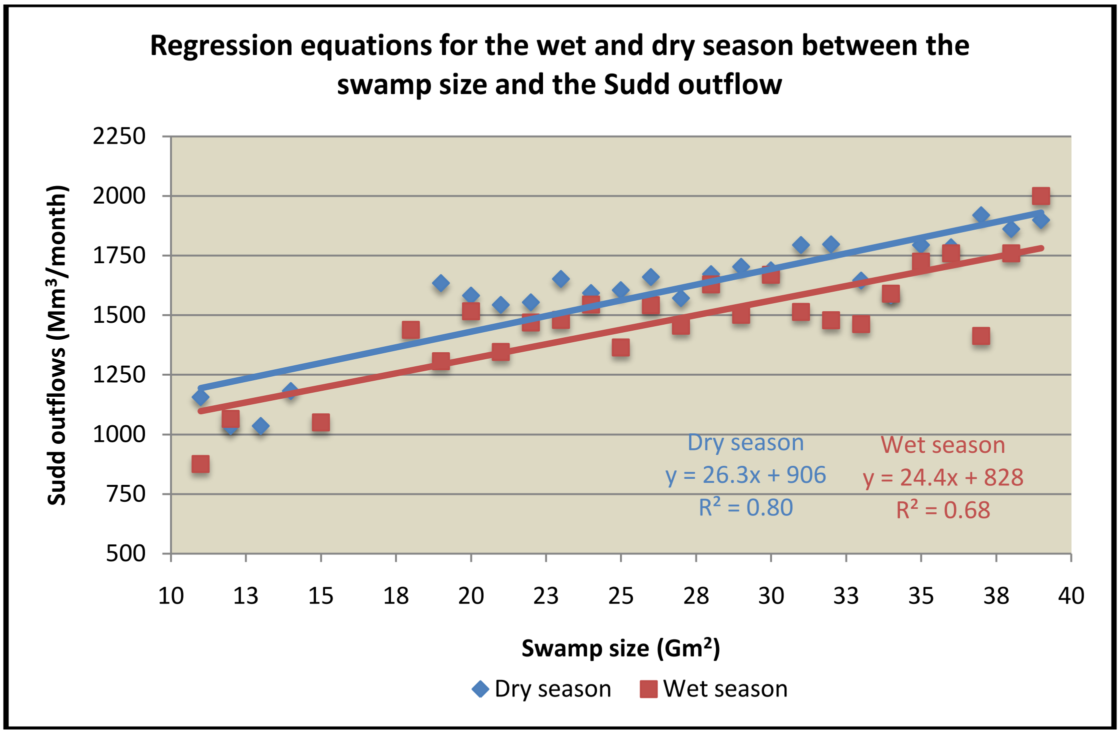

Figure 20 *The relation between the total swamp size and the Sudd outflow*

The dots in figure 24 are collected from the results from the simulated historic water balance. For every swamp size there will be different outflows. In the analysis, all the outflows for a single swamp size have taken together and have been averaged. This way you get for every swamp size a single average outflow, as can been seen in figure 24. A distinguishment has been made between a dry period and a period, because of the seasonality of the Sudd swamps. The regression lines nicely match the dots (R^2 is 0.80 and R^2 is 0.68), which makes it reliable that there is a linear relation between the total swamp size and the Sudd outflow.
To check the reliability of the regression lines, the Sudd outflows used in the historic water balance will be compared to the outflows that come out the regression equation based on the swamp sizes. The results are shown in figure 25:

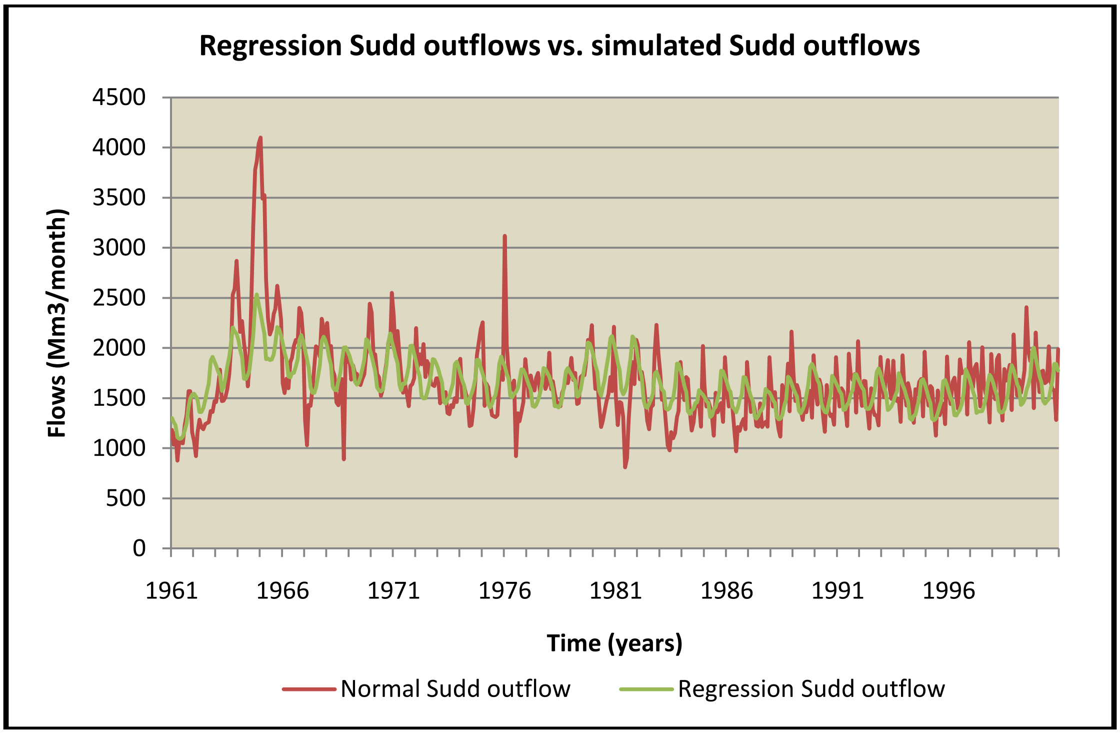

Figure 25 *The regression of the Sudd outflows vs. the normal Sudd outflows*

Figure 25 shows the comparison between the Sudd outflows simulated by the regression equation and the normal Sudd outflows. As can be seen, the Sudd outflows out the regression equation are quite smoother than the Sudd outflows used in the historic water balance. This is caused by the effect that the regression equation will smooth the extreme outflows in the normal Sudd outflows. The outflows show a correlation of 0.65, which can be considered as quite good.

With the equation for the regression between the swamp size and the Sudd outflow, the Sudd outflow can be simulated based on changed swamp sizes due to different Jonglei canal scenarios.

- **Evapotranspiration**

  The implementation of the Jonglei Canal will result in a drop of the relative humidity. When the whole Sudd will be drained the relative humidity will drop with 40 % in the dry season (Mohamed, 2005). Due to the fact that only about 25 percent of the normal inflow will be diverted through the Jonglei canal, it will be assumed that the relative humidity will drop by 10 percent in the dry season. One of the main reasons for this may be subscribed to the oasis effect. This effect is created when wet areas are surrounded by relatively dry areas. The wind will blow more soil moisture from the wet area to the dry area, resulting in a decrease of the relative humidity. As a result the evapotranspiration also will increase, as shown in figure 26.

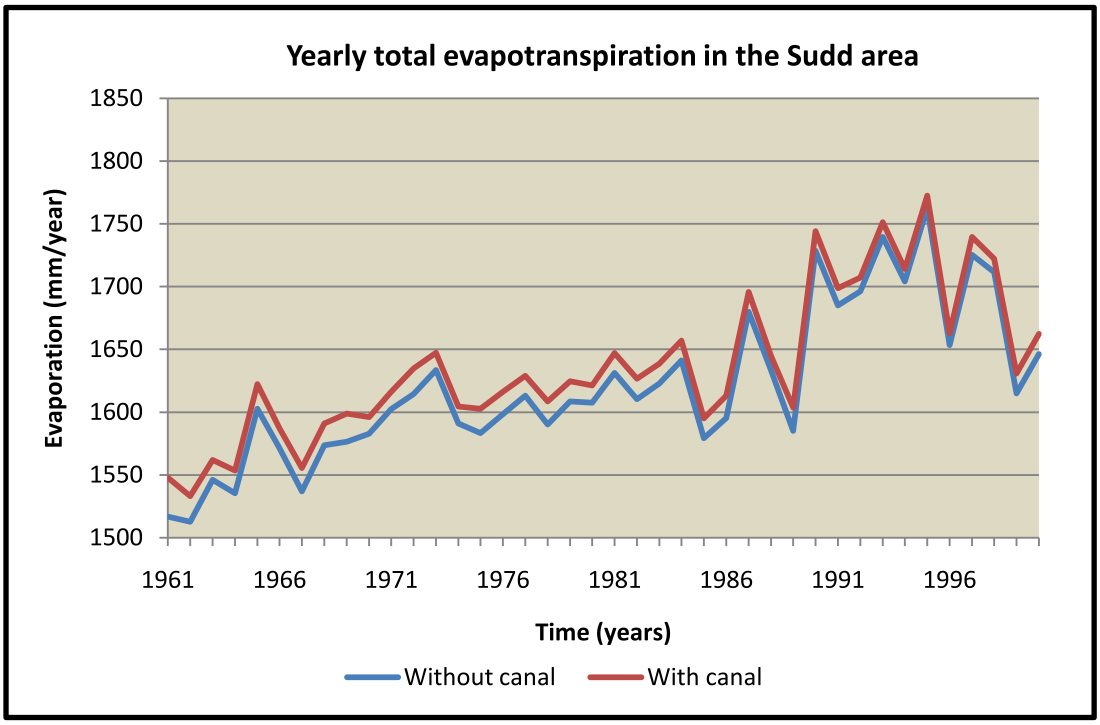

Figure 26 *The change in evaporation in the Sudd as a result of the Jonglei Canal*

Figure 26 shows the results from decreasing the relative humidity in the Sudd area. As expected, a lower relative humidity, results in less water parts in the air, whereby more water can be obtained to the air, causes higher evaporation rates.

With these adjustments for the inflow, Sudd outflow and the evapotranspiration, several Jonglei Canal scenarios can be simulated.

The different scenarios will be tested on these three criteria:

1. The change of the size of the swamp
2. The yearly extra water that will be available downstream of the Sudd
3. The change of the relation between the permanent and seasonal swamp

9.5 Set of scenarios I: Fixed canal flows

The Jonglei canal, when completed, is planned to carry about 20 Mm^3/day past the Sudd and save downstream about 4.8 Bcm/year of water currently evaporated in the swamps. To look at the effects of different fixed canal flows, the starting canal flow will be 20 Mm^3/day, as planned. Besides this canal flow, an extra 5 Mm^3/day will be tested, as well as a minus 5 Mm^3/day of the planned canal flow.

The fixed discharges that will be tested are:

- 15 Mm^3/day
- 20 Mm^3/day
- 25 Mm^3/day

The effects on the size of the swamps

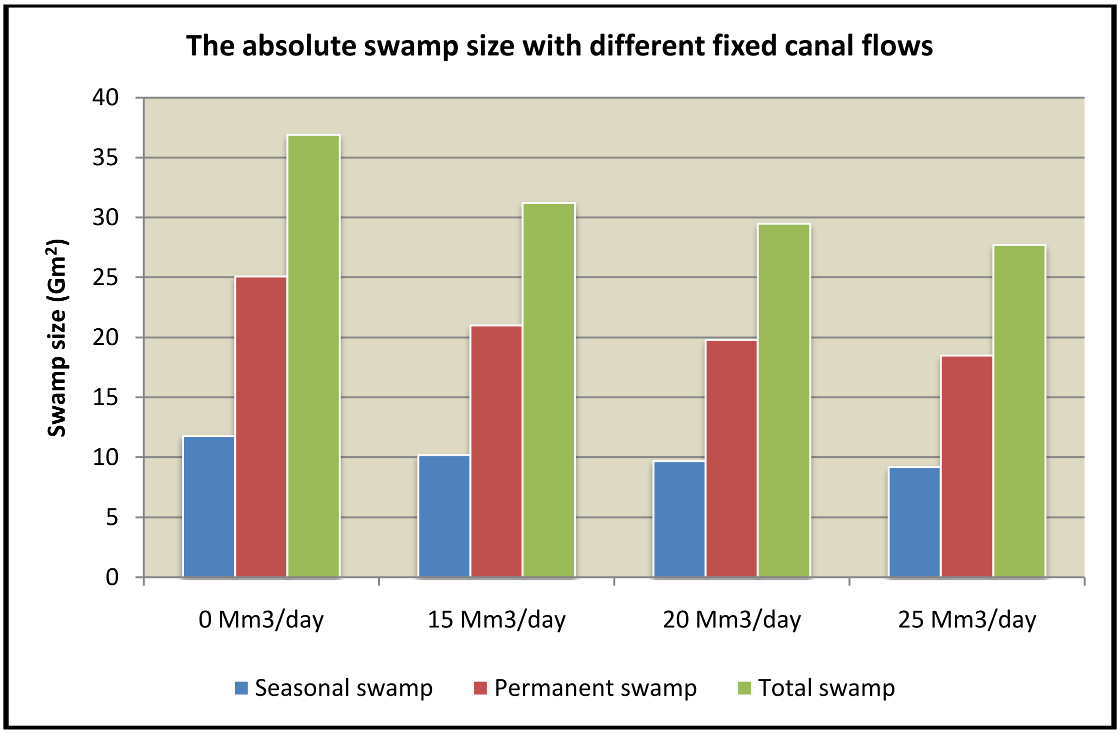

Figure 27 *The absolute swamp sizes with different fixed canal flows*

Scenario (Mm^3/day)	ΔPermanent swamp (-%)	ΔSeasonal swamp (-%)	ΔTotal swamp (-%)
15	16.3	13.5	15.4
20	21.3	17.8	20.2
25	26.4	22.0	25.0

Table 6 *The effect of different fixed canal flows on the swamp sizes*

Table 6 shows the fractional changes of the different swamp types as a result of the fixed canal flows. The permanent, seasonal and total swamps show a high linear relation with the size of canal flow. The effects on the size of the permanent swamp will be the highest, than the total swamp and the lowest on the seasonal swamp.

The effects on the extra available water downstream of the Sudd

Scenario (Mm^3/day)	ΔWater volume *Dry period* (Gm^3)	ΔWater volume *Wet period* (Gm^3)	ΔWater volume *Yearly* (Gm^3)	Extra available water (%)
15	1.9	2.1	4.0	19.7
20	2.5	2.8	5.3	26.5
25	3.1	3.5	6.6	33.3

Table 7 *The effects on the extra available water downstream of the Sudd with fixed canal flows*

With fixed canal flows there will be more water available downstream of the Sudd. With a canal flow of 15 Mm^3/day there will be 4.0 Gm^3 (or 19.7 %) water yearly extra available, with 20 Mm^3/day yearly 5.3 Gm^3 (or 26.5 %) extra water and with 25 Gm^3/day yearly 6.6 Gm^3 (or 33.3 %) extra water. An extra Mm^3/day canal flow will result in a yearly extra water volume of around 0.1 Gm^3.

The effects on the relation seasonal/permanent swamp

Scenario (Mm^3/day)	Relation permanent/seasonal swamp (%)
0	68.0/32.0
15	67.3/32.7
20	67.1/32.9
25	66.8/33.2

Table 8 *The effects on the relation seasonal/permanent swamp with fixed canal flows*

The effects on the relation between the seasonal and permanent swamp are relatively small. When there is a canal flow of 25 Mm^3/day, the relation will only change with 1 %. The permanent swamp is decreasing fractional more than the seasonal swamp (see table 8) which result in a smaller percentage of the permanent swamp in relation to the total swamp. Also can be observed, that all effects of the canal flow of the Sudd are a linear relation of the flow volume.

9.6 Set of scenarios II: Seasonal dependent canal flows

With seasonal dependent canal flows, the change of the size of the swamp can be regulated. Some actors will favor for a small shrinkage in the seasonal swamp (pastoralists), other will favor the permanent swamp (fisheries) and other will favor the total swamp (ecologists). The same amount of canal flows as used in scenario I will be tested as seasonal dependent canal flows.

The seasonal dependant canal flows that will be tested are:

- 25 Mm^3/day during the wet season (April - September) and 20 Mm^3/day during the dry season (October - March) and vice versa.
- 20 Mm^3/day during the wet season and 15 Mm^3/day during the dry season and vice versa.
- 15 Mm^3/day during the wet season and 25 Mm^3/day during the dry season and vice versa.

The effects on the size of the swamps

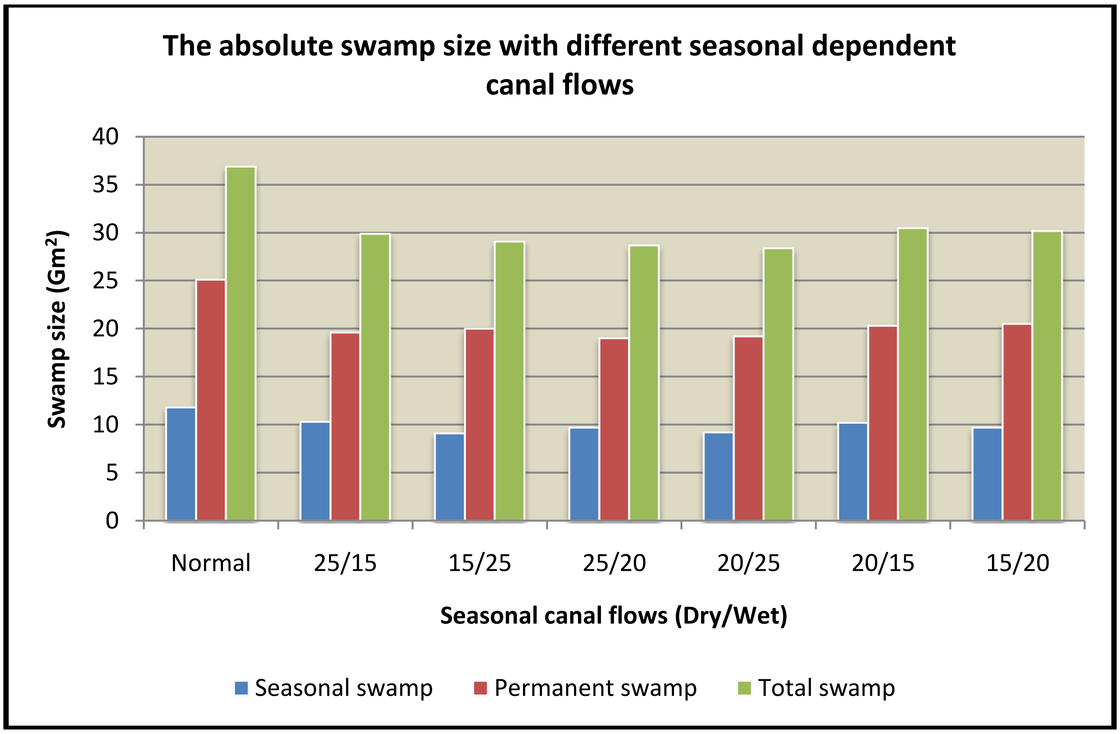

Figure 28 *The absolute swamp size with different seasonal canal flows*

Scenario (Q_{Dry}-Q_{Wet}) (Mm³/day)	ΔPermanent swamp (-%)	ΔSeasonal swamp (-%)	ΔTotal swamp (-%)
20 - 15	19.1	13.3	17.3
15 – 20	18.3	18.0	18.2
25 – 15	22.1	13.1	19.2
15 – 25	20.5	22.5	21.1
25 – 20	24.2	17.5	22.1
20 - 25	23.4	22.3	23.1

Table 8 *The effects of different seasonal canal flows on the swamp sizes*

The seasonal dependent flows show the largest effects on the change of the seasonal swamp. The change on the permanent swamp depends mainly on the total yearly flow of $Q_{dry} + Q_{wet}$. When this is high, the fractional decrease of the permanent swamp will also be high. The change of the seasonal swamp depends on the size of Q_{wet}. When this is high, the fractional decrease of the seasonal swamp will also be high. The change on the total swamp depends, just like the permanent swamp, on the total yearly flow of $Q_{dry} + Q_{wet}$.

The effects on the extra available water downstream of the Sudd

Scenario (Q_{Dry}-Q_{Wet}) (Mm^3/day)	ΔWater volume *Dry period* (Gm^3)	ΔWater volume *Wet period* (Gm^3)	ΔWater volume *Yearly* (Gm^3)	Extra available water (%)
20 - 15	2.2	2.3	4.5	23.1
15 – 20	2.2	2.3	4.5	23.1
25 – 15	2.5	2.8	5.3	26.5
15 – 25	2.5	2.8	5.3	26.5
25 – 20	2.8	3.0	5.8	29.9
20 - 25	2.8	3.0	5.8	29.9

Table 9 *The effect on the extra available water downstream of the Sudd with seasonal canal flows*

The extra available water downstream of the Sudd depends on the average flow of Q_{dry} and Q_{wet}. With an average flow of 17.5 Mm^3/day (or 23.1 %) there will be 4.5 Gm^3 (or 26.4 %) yearly extra available and with an average flow of 22.5 Mm^3/day there will be 5.8 Gm^3 (or 29.9 %) yearly extra available.

The effects on the relation seasonal/permanent swamp

Scenario (Q_{dry} – Q_{wet}) (Mm^3/day)	Relation permanent/seasonal swamp (%)
0	68.0/32.0
20 – 15	66.5/33.5
15 – 20	68.0/32.0
25 - 15	65.5/34.5
15 - 25	68.6/31.4
25 - 20	66.2/33.8
20 - 25	67.7/32.3

Table 10 *The effects on the relation seasonal/permanent swamp for seasonal canal flows*

Again the changes on the relation seasonal/permanent swamp are relatively small. The higher Q_{dry} is, the higher the fraction of the seasonal is in the total swamp. When Q_{wet} is higher, the fraction of the permanent swamp in the total swamp will be higher.

9.7 Set of scenarios III: Extra 4.8 Gm³/year water downstream of the Sudd

The last scenarios that will be tested are the scenarios each fulfilling the requirements of an extra volume of water of 4.8 Gm³/year downstream needed. This will be tested with a fixed canal flow and several seasonal dependent canal flows.
From table 7 can be estimated that a fixed canal flow of 18 Mm³/day will result in an extra water volume downstream of 4.8 Gm3/year. This means that there will be a canal flow of 18 Mm³/day during the wet period and 18 Mm³/day during the dry period. With that in mind, some seasonal dependent canal flows can be tested. The annual average of the canal flow need to be 18 Mm³/day (Q_{wet} + Q_{dry}) when creating canal flow scenarios.

The effects on the size of the swamps

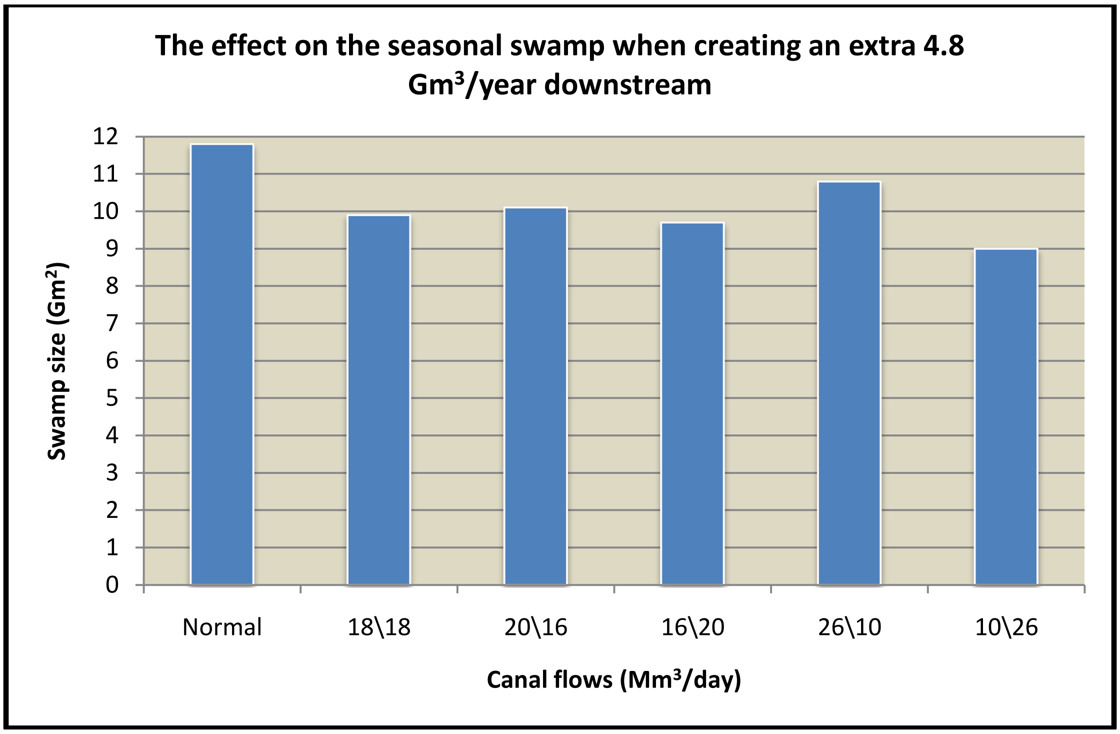

Figure 29 *The effects on the seasonal swamp when creating an extra 4.8 Gm³ downstream*

Scenario (Q_{Dry}-Q_{Wet}) (Mm³/day)	ΔPermanent swamp (-%)	ΔSeasonal swamp (-%)	ΔTotal swamp (-%)
20 – 16	19.5	14.2	17.8
16 – 20	18.9	18.0	18.6
26 – 10	20.5	8.5	16.7
10 - 26	18.0	24.6	19.8
18 – 18	19.2	16.1	18.2

Table 11 *The effects of different canal flows on the swamp sizes when creating an extra 4.8 Gm³/year downstream*

The scenario *10 – 26* has the highest influence on the change on the total swamp, almost 20 %. Scenario *10 – 26* also has the highest influence on the change on the seasonal swamp. The change of the permanent swamp will be the highest when scenario *26 – 10* will be used, although the difference between the scenarios are small.

From a fisherman's perspective, scenario *10 – 26* will be in favor, because the decrease of the permanent swamp will be at its lowest. From a pastoralist's perspective, scenario *26 – 10* will be in favor, because the decrease of the seasonal swamp will be at its lowest. From an ecologist's perspective, scenario *16 – 20* will be in favor, because the decrease of the total swamp will be at its lowest.

The effects on the relation seasonal/permanent swamp

Scenario (Q_{dry} – Q_{wet}) (Mm³/day)	Relation permanent/seasonal swamp (%)
0	68.0/32.0
20 – 16	66.6/33.3
16 – 20	67.8/32.2
26 – 10	64.9/35.1
10 – 26	69.6/30.4
18 – 18	67.2/32.8

Table 12 *The effects on the relation seasonal/permanent swamp when creating an extra water of 4.8 Gm³/year downstream*

Just like the other set of scenarios, the effects on the relation permanent/seasonal swamp will be small. A higher Q_{dry} results in a higher fraction of the seasonal swamp in the total swamp. A higher Q_{wet} results in a higher fraction of the permanent swamp in the total swamp.

9.8 Conclusions on the operating scenarios of the Jonglei Canal

The following conclusions can be made, when looking at the results of the tests:

Fixed canal flows

- A highly linear relation between size of the canal flows and the permanent, seasonal and total swamp.
- The effects on the permanent swamp size will be the highest, followed by the total swamp size and at last the seasonal swamp size.
- An extra Mm³/day canal flow will result in a yearly extra water volume of around 0.1 Gm³.
- The relation will shift from 68/32 to around 37/33.

Seasonal dependant canal flows

- The strongest effects can be found on the size of the seasonal swamp.
- The change on the permanent swamp depends mainly on the average yearly canal flow of 1/2 * (Q_{dry} + Q_{wet}). When this is high, the fractional decrease of the permanent swamp will also be high.
- The change of the seasonal swamp depends on the size of Q_{wet}. When this is high, the fractional decrease of the seasonal swamp will also be high.
- The change on the total swamp depends, just like the permanent swamp, on the average yearly flow of 1/2 (Q_{dry} + Q_{wet}).
- The relation permanent/seasonal swamp will only change small.

Extra 4.8 Gm^3/year water downstream of the Sudd

- The scenario *10 – 26* has the highest influence on the change on the total swamp, almost 20 %.
- Scenario *10 – 26* also has the highest influence on the change on the seasonal swamp.
- The change of the permanent swamp will be the highest when scenario *26 – 10* will be used, although the difference between the scenarios are small.
- Just like the other set of scenarios, the effects on the relation permanent/seasonal swamp will be small. A higher Q_{dry} results in a higher fraction of the seasonal swamp in the total swamp. A higher Q_{wet} results in a higher fraction of the permanent swamp in the total swamp.

In the table below the favored scenario is shown for the different actors in the Sudd region:

Actor	Favored scenario (Mm^3/day)
Fisherman	10 – 26
Pastoralist	26 - 10
Ecologist	16 - 20

Table 13 *The favored scenario for different actors*

As can be seen, the actors have different favored scenarios. This means that there is not one scenario that will fit every actors interests. The best scenario will be reached when actors will drop some of their criteria.

10. Discussions & Recommendations

10.1 Discussions

In this paragraph the used assumptions and result uncertainties will be discussed.

The research objective and question

- The research objective was to minimize the effects on the change of the size and seasonal cycle of the Sudd when analyzing different operating rules for the Jonglei Canal. Although it is obvious that higher canal flows result in stronger changes on the size and seasonal cycle, the objective has been accomplished. The criteria that were used to criticize the canal scenarios gave good insight in the overall effects on the Sudd swamps. The criteria that gave less effects than was expected, was the change on the relation between the permanent and seasonal swamp. The relation stayed stable for almost all canal scenarios. The effects on the change of the size of the different swamp sizes was expected. The results showed almost similar results with another study (Sutcliffe & Pars, 1987), although there were different data sets used (especially for the evapotranspiration). The effects on the extra gained water downstream showed good results compared with the literature; 20 Mm^3/day of canal flow should result in an extra water volume of 4.8 Gm^3, while at this study this was at 18 Mm^3/day.

The hydrological model

- The assumption was made that the average water level of the Sudd 1.0 meter was. Although studies (Sutcliffe & Parks, 1987) have been made to study other water levels and show that 1.0 m has been given the best results, there is still a high uncertainty in it. This is because the size of the water level has a high influence on the storage volume and swamp area.
- In this study the Sudd area has been divided in two parts to give more accurate results in the water balance. It could be that when the Sudd is taken as a whole, the results show better similarities with the reality.
- The last discussion point in the hydrological model was the definition of the different swamp types. The permanent swamp was defined as the lowest swamp size in a certain year. The seasonal swamp was defined as the highest swamp size minus the permanent swamp size. With these definitions certain restrictions have been set to calculate the sizes of the types. With other definitions, the results could show large differences.

Precipitation

- The most important point of discussion is the choice for the Global Precipitation Climatology Centre as the source of the data for the precipitation in the Sudd. There are more sources (like the Sudan meteorological ground stations data and the Famine Early Warning System (FEWS)) that provide precipitation data sets for the Sudd area. The choice was made for the GPCC, because of the high accuracy of the data sets and the possibility to collect monthly data for the whole period 1961 – 2000.

Evapotranspiration

- Although the Penman-Monteith equation the most used equation is to calculate evapotranspiration rates, there are other equations available to calculate the evapotranspiration (e.g. Priestley-Taylor and Hargreaves equations (APES, 2009)). The choice was made for the Penman-Monteith equation, because of the availability of data sets for the temperature, relative humidity and sunshine hours in the Sudd area. These data can serve as input in the Penman-Monteith equation.

- To calculate the evapotranspiration the assumption was made that the calculation for the area Bor – Malakal was represented by the averages of the data sets at Juba and Malakal. The calculation for the area Mongalla – Bor the assumption was made that it was represented by the averages of the data sets only at Juba. These choices were made based on the topographical place of these stations compared to the area.

Inflow and outflow

- The regression lines for both the inflow as outflow are questionable, because of the high uncertainties they have. Although some regression lines show low values of R^2, the lines that were picked showed the least variance with the data points. At the end, the uncertainty will remain in the equations, but is accepted to be part of the calculation for the inflow and outflow.

The water balance

- The most important point of discussion is the verification of the Sudd swamp sizes with the collected satellite images. It was only possible to collect satellite images for five different dates, because the other taken images were incompetent for further analysis. The collected images were analyzed based on counting the parts of the images that consisted of swamps. This counting has high uncertainties, because of the subjectivity of it. In some cases it was impossible to distinguish swamp area with other parts. Although the verification has high uncertainties, it was the only way to verify the simulated swamp sizes.

Jonglei canal scenarios

- Based on the results of Mohamed (2005) where the whole Sudd would be drained and the relative humidity would drop with 40 % in the dry period, the assumption was made that in this study the relative humidity would drop with 10 %, because the Sudd would only be drained for 25 %. This relation is highly questionable, because the relation could not be linear as assumed.
- Another point of discussion is the relation that was made between the Sudd swamp sizes and outflows. The relation was split in two, because of the high seasonality of the swamp sizes. There are other ways to relate these two variables, but based on the seasonality the choice was made to use two regression lines.

10.2 Recommendations

In this paragraph some recommendations will be made for further study.

- Instead of using the Penman-Monteith equation to simulate the evapotranspiration data, SEBAL calculations can be made to get more accurate data about the evapotranspiration.
- Other regression lines can be used for the relation between the swamp sizes and outflow to simulate the water balance for different canal scenarios. Also the engaging of the inflow in this relation can be something to consider.
- Precipitation data sets from other sources can be used.

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Appendix

Appendix A *Calculation of ET_0*

The reference evapotranspiration from meteorological data is assessed in the ET_0 Calculator software by means of the FAO Penman-Monteith equation. This method has been selected by FAO as the reference because it closely approximates grass ET_0 at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters.

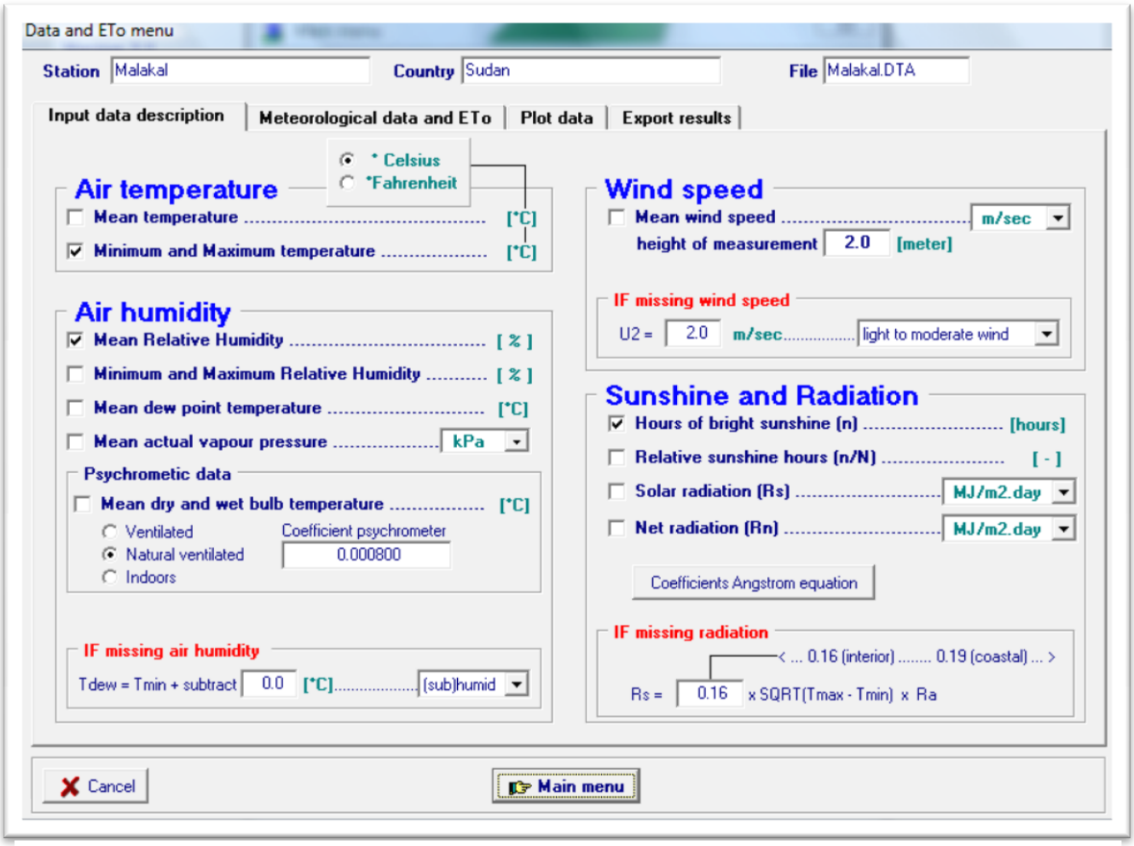

Figure 30 *The different parameters in the ET_0 calculator from FAO (2009)*

The figure above shows the parameters that are needed to calculate ET_0:

Air temperature

The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature. The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration. In sunny, warm weather the loss of water by evapotranspiration is greater than in cloudy and cool weather.

The daily maximum air temperature (T_{max}) and daily minimum air temperature (T_{min}) are, respectively, the maximum and minimum air temperature observed during the 24-hour period, beginning at midnight. The mean daily air temperature (T_{mean}) is only employed in the FAO Penman-Monteith equation to calculate the slope of the saturation vapour pressure curves (Δ) and the impact of mean air density (P_a) as the effect of temperature variations on the value of the climatic parameter is small in these cases. For standardization, T_{mean} for 24-hour periods is defined as the mean of the daily maximum (T_{max}) and minimum temperatures (T_{min}) rather than as the average of hourly temperature measurements.

$$T_{mean} = \frac{T_{max} - T_{min}}{2}$$

With T_{max} and T_{min} in degrees Celsius (°C).

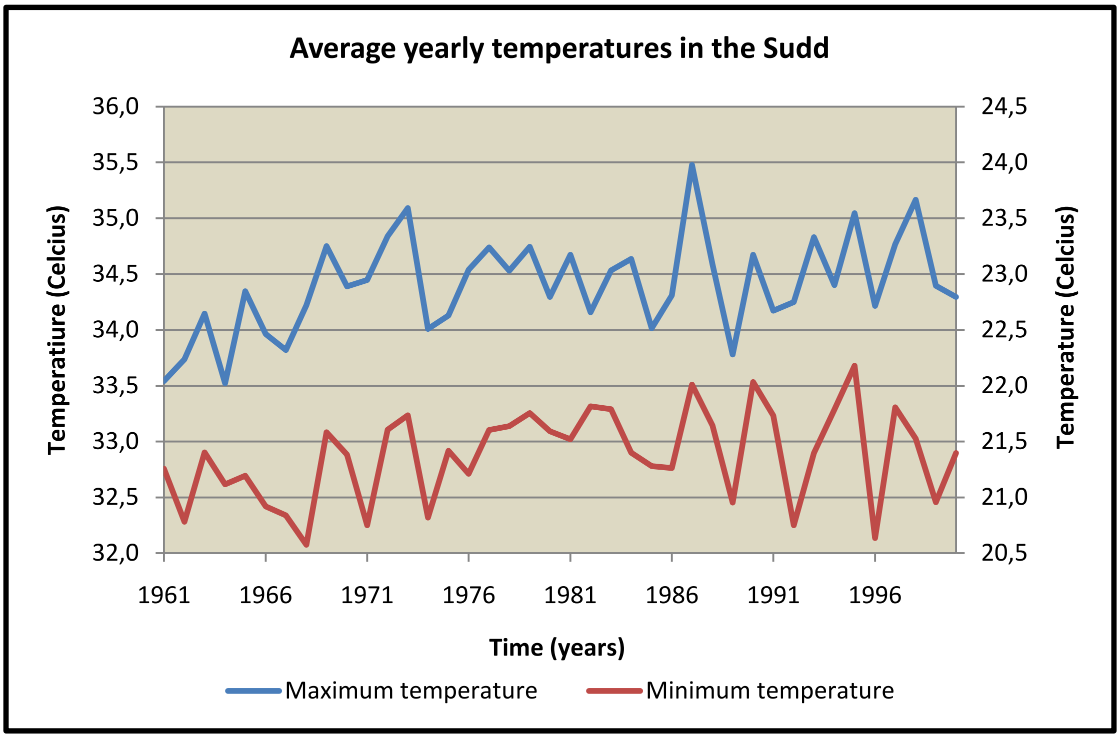

Figure 31 *The minimum and maximum temperature in the Sudd*

In figure 31 the minimum and maximum temperature in the Sudd during the period 1961 – 2000 are shown from measurement stations Juba and Malakal. The minimum temperature fluctuates between 20.5 and 22 °C, while the maximum temperature reaches between 33.5 and 35.5 °C. The data shows no clear trend during the period, although the temperatures between 1975 and 1985 are relatively stable compared to the rest of the period.

Air humidity

While the energy supply from the sun and surrounding air is the main driving force for the vaporization of water, the difference between the water vapour pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapour removal.

The relative humidity (RH) expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation ($e°(T)$) vapour pressure at the same temperature (T):

$$RH = 100\frac{e_a}{e^o(T)} \text{ in } [\%]$$

Relative humidity is the ratio between the amount of water the air actually holds and the amount it could hold at the same temperature. It is dimensionless and is commonly given as a percentage. Although the actual vapour pressure might be relatively constant throughout the day, the relative humidity fluctuates between a maximum near sunrise and a minimum around early afternoon. The variation of the relative humidity is the result of the fact that the saturation vapour pressure is determined by the air temperature. As the temperature changes during the day, the relative humidity also changes substantially.

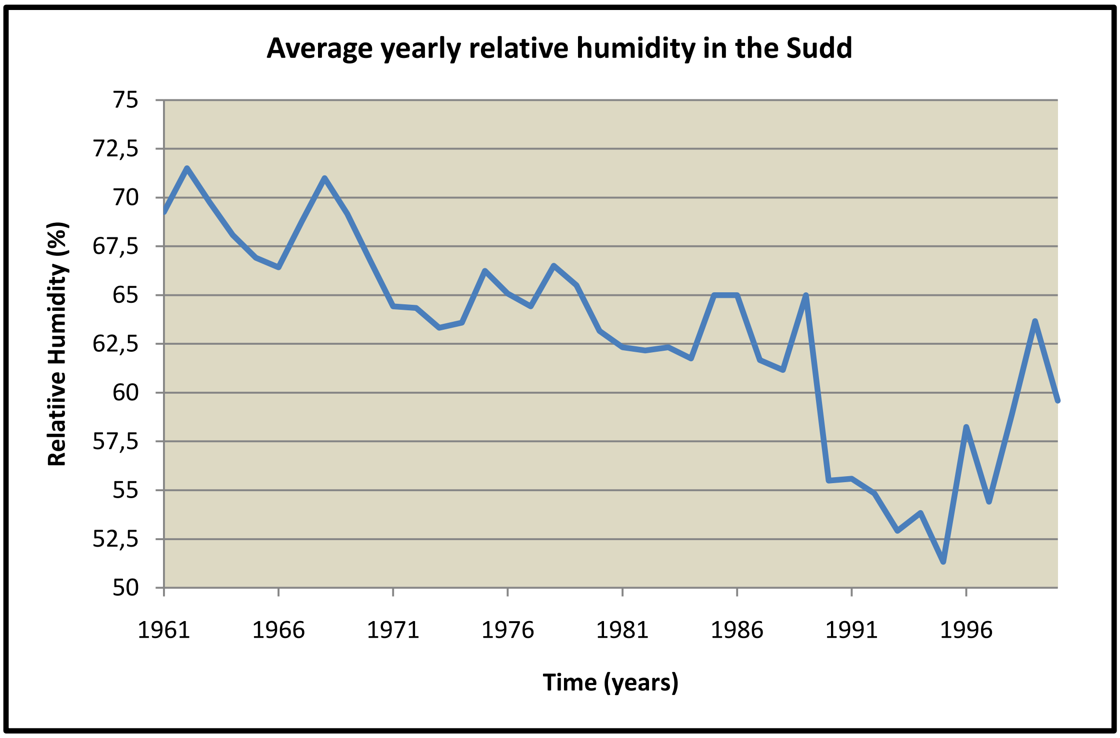

Figure 32 *The average yearly relative humidity in the Sudd*

As can been seen in figure 32 the relative humidity has dropped from 70 percent in the early 60s around 50 percent in 1995. After 1995 the relative humidity suddenly increased substantially setting it back on around 60 percent. This is caused by an increase in the solar radiation, as will be shown later on.

Wind speed

The (average) daily wind speed in meters per second (m s^{-1}) measured at 2 m above the ground level is required. The wind speed in the Sudd is mostly unknown, and therefore an average wind speed of 2 m/s will be used.

Sunshine and Radiation

The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation is the largest energy source and is able to change large quantities of liquid water into water vapour. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons.

Solar radiation, R_s

If the solar radiation, R_s, is not measured, it can be calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a$$

where,

R_s = solar or shortwave radiation [MJ m^{-2} day^{-1}]
n = actual duration of sunshine [hour]
N = maximum possible duration of sunshine or daylight hours [hour]
n/N = relative sunshine duration [-]
R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}]
a_s regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0)
$a_s + b_s$ fraction of extraterrestrial radiation reaching the earth on clear days (n = N)

R_s is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_s by 0.408. In the FAO Penman-Monteith equation, radiation expressed in MJ m^{-2} day^{-1} is converted to equivalent evaporation in mm day^{-1} by using a conversion factor equal to the inverse of the latent heat of vaporization ($1/\lambda = 0.408$).

Depending on atmospheric conditions and solar declination, the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values a_s = 0.25 and b_s = 0.50 are recommended.

Extraterrestrial radiation, R_a

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s sin(\varphi) sin(\delta) + cos(\varphi) cos(\delta) sin(\omega_s)]$$

Where,

R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}]
G_{SC} = solar constant [0.0820 MJ m^{-2} min^{-1}]
d_r = inverse relative distance Earth-Sun [-]
ω_s = sunset hour angle [rad]
φ = latitude [rad]
δ = solar decimation [rad]

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033 cos\left(\frac{2\pi}{365} J\right)$$

$$\delta = 0.409 sin\left(\frac{2\pi}{365} J - 1.39\right)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

The sunset hour angle, ω_s, is given by:

$$\omega_s = arccos[-tan(\varphi)tan(\delta)]$$

R_a is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_a by 0.408. The latitude, φ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by:

$$Radians = \frac{\pi}{180} decimaldegrees$$

The average yearly solar radiation shows the same pattern as the relative humidity in the Sudd area. This is clear, because the amount of the solar radiation influence the amount of relative humidity.

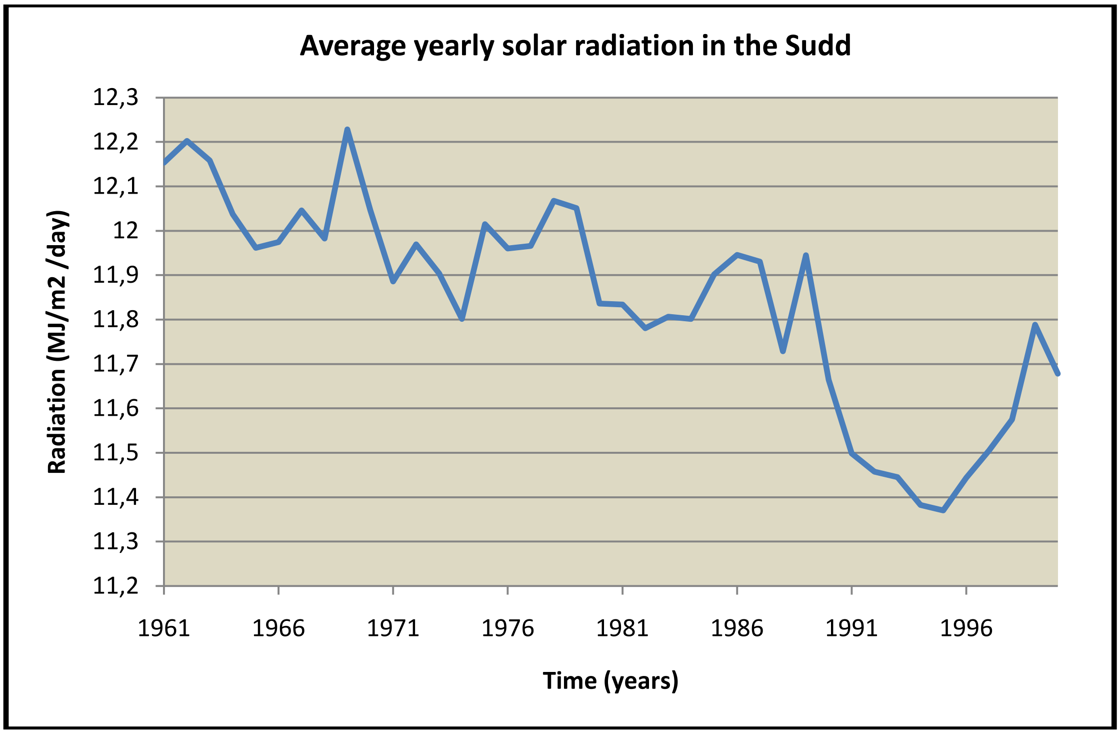

Figure 22 *The average yearly solar radiation in the Sudd*

All the data that was required to calculate the reference evaporation ET_o for the period 1961 – 2001 with the E_0 calculator (air temperature, air humidity, sunshine and radiation) is collected from the measurement stations Juba and Malakal.