

The Hydrology of the Sudd

Hydrologic Investigation and Evaluation of Water Balances in the Sudd Swamps of Southern Sudan

Dissertation

zur Erlangung des Doktorgrades
der Mathematisch-Naturwissenschaftlichen Fakultät
der Christian-Albrechts-Universität
zu Kiel
vorgelegt von

Georg Petersen, MSc.

Kiel

2008

Referentin: Prof. Dr. Nicola Fohrer

Koreferent: Prof. Dr. Hans-Rudolf Bork

Tag der mündlichen Prüfung:

Zum Druck genehmigt:

Der Dekan

Danksagung

Mein ausdrücklicher Dank für eine superbe Betreuung gilt Nicola Fohrer, ohne deren sehr positive Unterstützung ein erfolgreicher Abschluss dieser Arbeit nicht möglich gewesen wäre.

Weiterer Dank gilt Ole Larsen von DHI Deutschland für die Überlassung einer Mike 21 Lizenz sowie meinen Kollegen bei HR Wallingford die mir stets mit hilfreichen Ratschlägen und guten Ideen für Ansätze zu Problemlösungen beigestanden haben.

Ein ganz großer Dank gebührt auch Fiona und John Sutcliffe für die vielen Dinners und Diskussionen sowie unzählige Anstöße und Ratschläge.

Der Grundstein meiner Arbeit wurde jedoch im Sudan gelegt. Mein Dank hier gilt meinen Kollegen bei USAID, USDA, der UN und der GTZ, aber ganz besonders den Menschen in Padak, die mir die Feldarbeit und Datensammlung in den Sudd Sümpfen erst ermöglicht haben.



Cattle camp near Padak in southern Sudan

Summary

This dissertation describes the hydrology of the Sudd swamps in southern Sudan, comprising a hydrologic investigation and evaluation of its water balance. The study improves historical interpretations and unveils so far unknown conditions and interdependencies in the swamp and floodplain system, considering the area morphology, vegetation dynamics, water balance, flow conditions and hydrodynamic processes in the system. The assessment is based on field works carried out in the swamps over a three year period between 2004 and 2006 as well as historical and remote sensing data.

Interdependencies between morphology and hydrology are described considering the effect of ground slopes and morphological features on spill and flooding of the seasonally flooded grasslands. Bathymetric depth profiles and cross sectional depth and flow distributions have been established for the Sudds inland delta and the question of spill into the Bahr el Ghazal basin has been assessed. Vegetation dynamics in the swamp have been described and quantified assessing the extent of changes in the channel and lagoon system of the Sudd using Landsat satellite images for water body delineation. Changes in-between years and as well compared to Lake Victoria outflow data have been established and quantified; correlation was found for the largely water level dependent lagoon system. Variations in the channel system were interpreted to happen in a certain pattern but the extent of changes could not be correlated to the outflow data as they are influenced by additional, here not considered factors like wind drift and channel blockages by vegetation.

The water balances of the floodplains, while controlled by river levels, were found to be dependent on a complex interaction between soil, vegetation, topography and seasonal trends in rainfall and evapotranspiration. Based on field measurements, these components have been assessed in detail and evaluated regarding their function in the seasonal cycle of flooding and drying. An analysis of the soil and evapotranspiration conditions as well as the interaction with vegetation and meteorological conditions using field and laboratory experiments was conducted. Sources, processes, flow directions and the fate of the floodwaters on both the river fed seasonal floodplains and the rainfed grasslands have been established showing that river spill is responsible for area flooding while no return flow occurs and drying is caused by evapotranspiration alone. Additionally it was found that rainfall can only cause temporary flooding in extreme events.

To obtain missing flow data for important but ungauged locations, methods have been established to derive these, combining upstream flows from Lake Albert and torrential runoff derived from the Collaborative Historical African Rainfall Model (CHARM) rainfall data in the catchment between Lake Albert and Mongalla. The results provide previously unavailable flow data at Mongalla, the entry to the Sudd swamp, with a high level of confidence; data which are essential for detailed hydrological assessments of the swamp system. In addition to evaluations based on measurements, a numerical hydrodynamic assessment has been carried out with the DHI MIKE21 model. The study has established water level gradients, flow directions and velocities in the swamp as well as on the seasonal floodplains.

Zusammenfassung

Diese Dissertation beschreibt die Hydrologie der Sudd Sümpfe im Süd-Sudan und besteht aus einer hydrologischen Untersuchung und Auswertung der Wasserbilanz. Die Arbeit verfeinert historische Interpretationen und beschreibt bisher unbekannte Bedingungen und Zusammenhänge in den Sumpf- und Überschwemmungsgebieten unter Berücksichtigung von Morphologie, Vegetationsdynamik, Wasserbilanz, Fließbedingungen, und hydrodynamischen Prozessen. Die Untersuchungen basieren auf dreijährigen Feldarbeiten von 2004 bis 2006 sowie historischen- und Fernerkundungsdaten.

Zusammenhänge zwischen der Morphologie und Hydrologie sind unter Berücksichtigung der Effekte von Gefälle und morphologischen Besonderheiten auf die Überflutungscharakteristik in den saisonal überfluteten Grassflächen beschrieben. Wassertiefenprofile, Querschnittstiefen und Fließprofile wurden für das Sudd Inland-Delta erstellt und die Frage nach Überlauf in das Bahr el Ghazal Becken untersucht. Die Vegetationsdynamik in den Sümpfen wurde durch Untersuchungen von Veränderungen des Kanal- und Lagunensystems beschrieben und quantifiziert; Die Untersuchungen basieren auf Landsat Satellitenbildern welche zur Feststellung von Veränderungen zwischen verschiedenen Jahren und im Vergleich zum Lake Victoria Ausfluss benutzt wurden. Eine Übereinstimmung für das hauptsächlich wasserspiegelabhängige Lagunensystem wurde gefunden. Bei Veränderungen im Kanalsystem konnte ein Änderungsmuster festgestellt werden, ein direkter Zusammenhang mit Änderungen des Lake Victoria Ausflusses wurde nicht gefunden, da noch andere, hier nicht untersuchte Faktoren wie Winddrift und Kanalblockaden durch Vegetation eine Rolle spielen.

Die Wasserbilanz der Überflutungsflächen ist, obwohl grundsätzlich abhängig von Fluss-Wasserständen, von komplexen Interaktionen zwischen Boden, Vegetation, Topographie, und saisonalen Trends von Niederschlag und Evapotranspiration bestimmt. Diese Komponenten wurden, basierend auf Feldmessungen, detailliert untersucht und bezüglich ihrer Funktion im saisonalen Überflutungs- und Trocknungskreislauf ausgewertet. Eine Analyse von Boden und Evapotranspiration und deren Interaktion mit der Vegetation und meteorologischen Bedingungen wurde unter Nutzung von Feld- und Laborexperimenten durchgeführt. Ursprung, Prozesse, Fließrichtungen und Verbleib des Wassers auf sowohl den saisonalen Überflutungsflächen sowie den regengespeisten Grasebenen wurden festgestellt. Die Ergebnisse zeigen, dass Flusswasser für die Überflutungen verantwortlich ist und Flutwasser nicht ablaufen, sondern die Trocknung durch Evapotranspiration erfolgt. Es wurde des Weiteren festgestellt, dass auch extreme Niederschläge nur kurzfristige Überflutungen verursachen können.

Um Abflussdaten für wichtige, nicht gemessene Punkte zu erstellen, wurden Methoden zur Interpolation aus den Abflussdaten des flussaufwärts gelegenen Albert See Abflussdaten und Zuflüssen aus dem zwischen dem Albert See und Mongalla gelegenen Einzugsgebiet basierend auf CHARM (Collaborative Historical African Rainfall Model) entwickelt. Die Ergebnisse liefern neue Abflussdaten für das am Eingang der Sümpfe liegende Mongalla mit einem hohen Vertrauensniveau. Diese Daten sind für eine detaillierte hydrologische Untersuchung des Sumpfsystems unerlässlich. Zusätzlich zur Auswertung der Feldmessungen wurden numerisch-hydrodynamische Untersuchungen mit dem DHI MIKE21 Modell durchgeführt. Durch diese Studien wurden Wasserspiegelgradienten, Fließrichtungen und Strömungen in den Sümpfen und auf den saisonalen Überflutungsflächen berechnet.

Contents

Chapter I - Introduction	1
1.1 Overview	1
1.2 The Sudd swamps	2
1.3 Historical studies	6
1.4 Field work	9
1.5 Scope, structure and objectives of this study	9
Chapter II - Morphological analysis of the Sudd region using land survey and remote sensing data	11
<i>Earth Surface Processes and Landforms 33, 2008</i>	
<i>Submitted: 23.11.06, Accepted 01.11.07, Published 13.05.08</i>	
Abstract	11
2.1 Introduction	11
2.2 Materials and methods	12
2.2.1 The study site	12
2.2.2 Field assessment methods	14
2.2.3 Data analysis methods	16
2.3 Results	16
2.3.1 Morphological features	16
2.3.2 River bathymetry	17
2.3.3 Morphological analysis from SRTM Digital Elevation Model (DEM)	19
2.3.4 Evaluation of Landsat satellite images	23
2.4 Discussion	24
2.4.1 Interaction of morphology and hydrology	24
2.4.2 Cross sectional depth and flow distribution	24
2.4.3 SRTM analysis	25
2.5 Conclusion	26

Chapter III - Spatio-temporal water body and vegetation changes in the Nile swamps of southern Sudan	27
<i>Advances in Geosciences, Volume 11, 2007, Pages 113-116.</i>	
<i>Submitted 15.01.07, Accepted 22.05.07, Published 20.06.07</i>	
Abstract	27
3.1 Introduction	27
3.2 Methods	28
3.3 The system	28
3.4 Results	30
3.5 Discussion	33
3.6 Conclusions and future perspective	34
Chapter IV - Water balances of the Vertisol floodplains of southern Sudan	35
<i>Hydrological Sciences Journal</i>	
<i>Submitted 19.11.07</i>	
Abstract	35
4.1 Introduction	35
4.2 Materials and methods	36
4.2.1 The study site	36
4.2.2 Geology	38
4.2.3 Soil Analysis	38
4.2.4 Soil water recharge	38
4.2.5 Soil Evaporation	39
4.2.6 Rainfall measurements	39
4.2.7 Recording of meteorological data	39
4.2.8 Water level records	39
4.2.9 Vegetation observations	40
4.2.10 Actual evapotranspiration	40
4.2.11 Evapotranspiration calculations	40
4.3 Results	41
4.3.1 Surface geology	41
4.3.2 Soil Analysis	42
4.3.3 Soil water recharge	43
4.3.4 Soil evaporation	44

4.3.5 Rainfall data	45
4.3.6 Other Meteorological data	45
4.3.7 Actual evapotranspiration	46
4.3.8 Evapotranspiration calculations	47
4.3.9 Vegetation condition	48
4.3.10 Observation of short distance water level fluctuations	48
4.4 Discussion of flooding and drying mechanisms	49
4.4.1 Components of flooding mechanism	49
4.4.2 Water budget of the floodplain areas	50
4.5 Conclusions	52
Acknowledgements	52
Chapter V - Estimating of ungauged Bahr el Jebel flows based on upstream water levels and large scale spatial rainfall data	53
<i>Advances in Geosciences</i>	
<i>Submitted 15.01.08, Accepted 11.04.08, In Press</i>	
Abstract	53
5.1 Introduction	53
5.2 Methods	55
5.2.1 Study area description	55
5.2.2 Approach to the problem and flow data sources	56
5.2.3 Rainfall time series and torrent flows based on CHARM data	58
5.2.4 Estimating Mongalla flows	58
5.3 Results	59
5.3.1 Lake Albert outflow	59
5.3.2 Torrent runoff and Mongalla flows	61
5.4 Discussion	61
5.5 Conclusions	62

Chapter VI - Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan	63
<i>Hydrological Sciences Journal</i>	
<i>Submitted 02.04.08</i>	
Abstract	63
6.1 Introduction	63
6.2 Materials and methods	64
6.2.1 The study site	64
6.2.2 Hydrological conditions	67
6.2.3 The DHI MIKE 21 model	68
6.2.4 Model setup, sensitivity and calibration	68
6.3 Results	70
6.4 Discussion	73
6.4.1 Model performance	73
6.4.2 Seasonal floodplain flows	74
6.4.3 Components of flooding cycle	75
6.5 Conclusions	76
Acknowledgements	76
Chapter VII - Summary and key findings	77
Chapter VIII - Discussion and conclusions	79
8.1 The Sudd swamp system	79
8.2 Conclusions and outlook	82
Bibliography	85
List of Figures	89
List of Tables	93

Chapter I - Introduction

1.1 Overview

The study of the hydrology of the Sudd comprises hydrologic investigation and the evaluation of water balances in the Sudd swamps of the Bahr el Jebel at the upper White Nile in southern Sudan. The study was carried out in the area between Mongalla and Shambe, mainly focusing on a core area between Bor and Mabiior. An overview is shown in Figure 1.1.

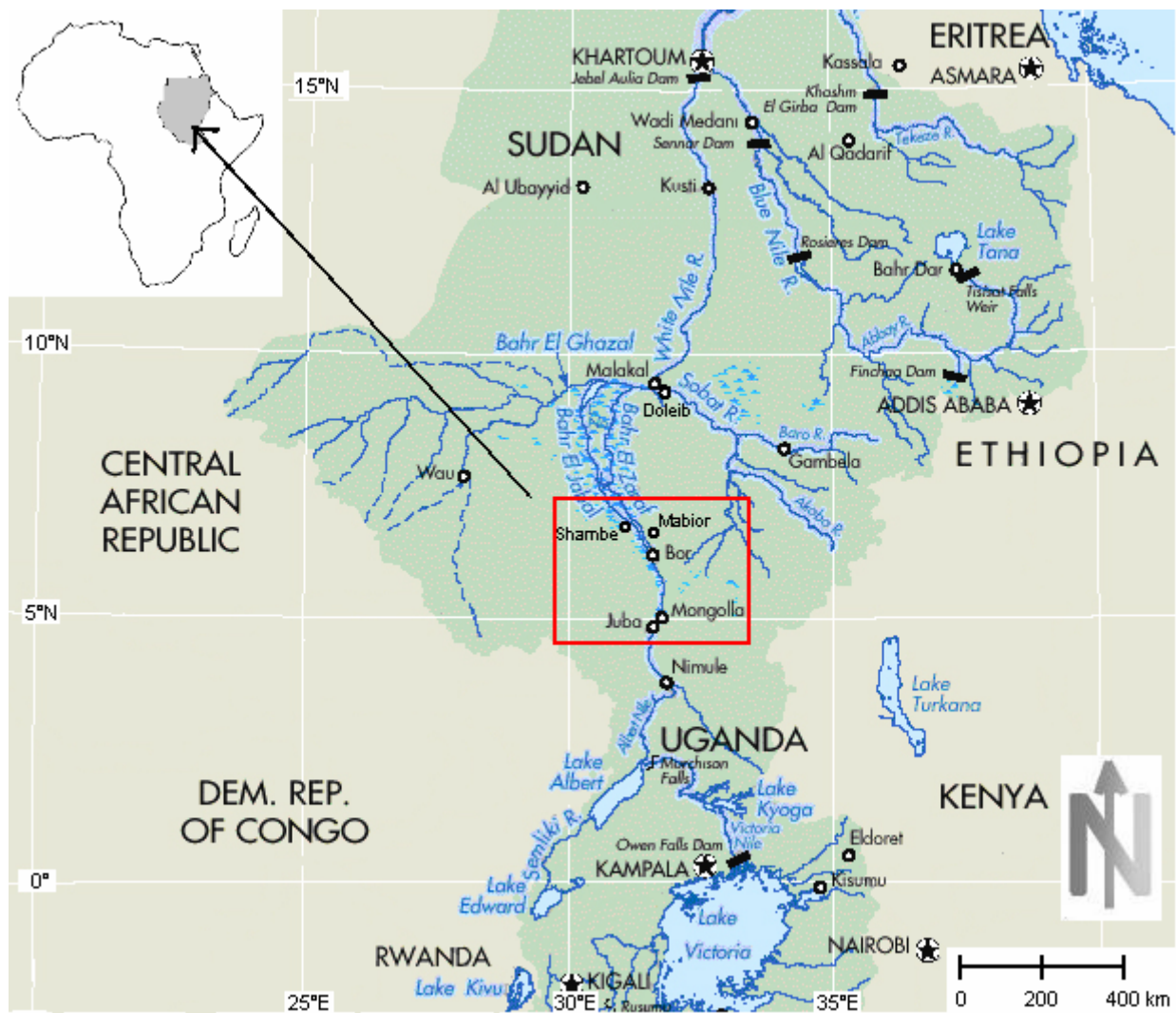


Figure 1.1: The Nile in southern Sudan with the core area of interest between Mongalla and Shambe (modified from World Bank, 2008)

The study was launched and information about the study area was obtained from assessments in line with a commencing road and dike rehabilitation project carried out by UN-WFP, starting in January 2004 in the Bor area. Assessments were conducted in various boat trips, drives, walks and flights in the area over a two year period between 2004 and 2006 giving an overall picture of the local situation. Echosounding campaigns, current measurements, the setup of a network of monitoring stations measuring water levels as well as meteorological parameters and the conduct of evapotranspiration-, soil evaporation- and soil water recharge experiments in the floodplain area were, next to regular observations and literature research, a vital base of the study.

1.2 The Sudd swamps

The Sudd area, one of the largest wetland areas worldwide, a shallow and very flat basin between 5.5 and 9.5 degrees north latitude, covers an area of approximately 30,000 km² over a length of 500 km south to north between Mongalla and Malakal. The area can be described as an inland delta and is highly variable in size depending on the inflowing waters, with the discharge from Lake Victoria being the main control factor of flood levels and area inundation. A main hydrological factor is also that within the Sudd area, consisting of various meandering channels, lagoons, reed- and papyrus fields as shown in Figure 1.2, half of the inflowing water is lost through evapotranspiration in the permanent and seasonal floodplains (Sutcliffe & Parks, 1999). A major feature of the area, even if not completed and not functional, is the Jonglei Canal, planned to bypass waters from the Sudd to avoid evaporation losses and increase the amount of water discharged to the north at the outlet of the Sudd.



Figure 1.2: Permanent swamp with active main channel, lagoons and papyrus area

The Sudd is the largest freshwater wetland in the Nile basin stretching from Mongalla in the south to near the Sobat confluence with the Nile just upstream of Malakal in the north as well as westwards along the Bahr el Ghazal (Figure 1.3). The size of the Sudd varies largely from season to season and year to year. From 1961 to 1963 a great increase in the inundated area

occurred when the level of Lake Victoria rose, causing a respective increase in discharge. The total area is related to the amount of water reaching Mongalla from Lake Victoria and from torrents or seasonal watercourses that can add substantial amounts to the flow at the upstream end of the Sudd. During the 1960 to 1964 increase in Lake Victoria discharge, flows at Mongalla have roughly doubled. The flows at Malakal at the northern end of the swamps had in the same time increased by 1.5 times the previous average flow. As a consequence of these high flows, the areas of permanent swamp and seasonal floodplains had, together, increased to 2.5 times their former size. The swamps have increased the most but even so the seasonal floodplain was 1.5 times its previous size (Mefit-Babtie, 1983).

From the southern inflow of the Bahr el Jebel at Mongalla, the defined riverbed successively widens into a floodplain, where the waters flow in meandering river stretches, various channels and lagoons throughout the dry season, expanding over the semi flooded grasslands during the flood season with rising water levels (Figure 1.3). Slightly downstream of Bor, the Bahr el Zeraf is branching of the Bahr el Jebel to the east, diverting part of the flow, to join the Bahr el Jebel again just before reaching Malakal. During the course of its flow, the Bahr el Jebel passes Lake No, where also the Bahr el Ghazal is connected to the Bahr el Jebel, contributing an inflow with seasonal variation. Just upstream of Malakal, the Sobat River joins into the system. The combined flows then stream to the north as the White Nile in a defined bed, joining with the Blue Nile waters at Khartoum to form the main Nile.

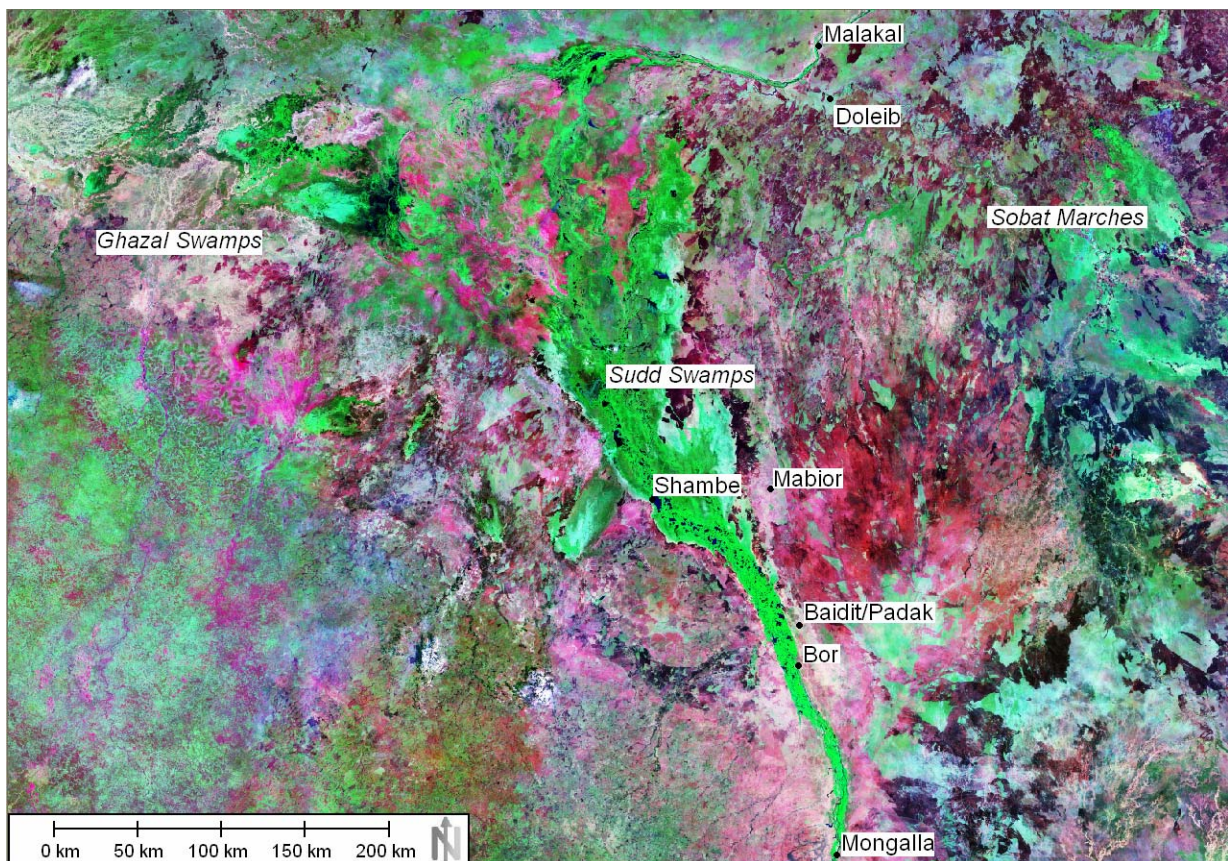


Figure 1.3: 2002 Landsat (NASA, 2006b) image of the Sudd area of southern Sudan in its full extent between the main historical gauging stations of Mongalla in the south and Malakal in the north. Most studies in this dissertation have been carried out between Bor and Shambe

Hydrologically, the Sudd plays an important role in storing floodwaters and trapping sediments from the Bahr el Jebel. As shown in Figure 1.4, an average 55 % of the waters entering the Sudd are lost by evapotranspiration and thus only half of the flow of the Bahr el Jebel at Mongalla reaches the northern outlet of the Sudd at Malakal (Baecher, 2000). Water level fluctuations can be found in a range of up to 1.5 meters, depending on the intensity of the floods. Typical precipitation values are 800 to 900 mm with evaporation values of 1500 mm and evapotranspiration values of up to 2150 mm (Mefit-Babtie, 1983).

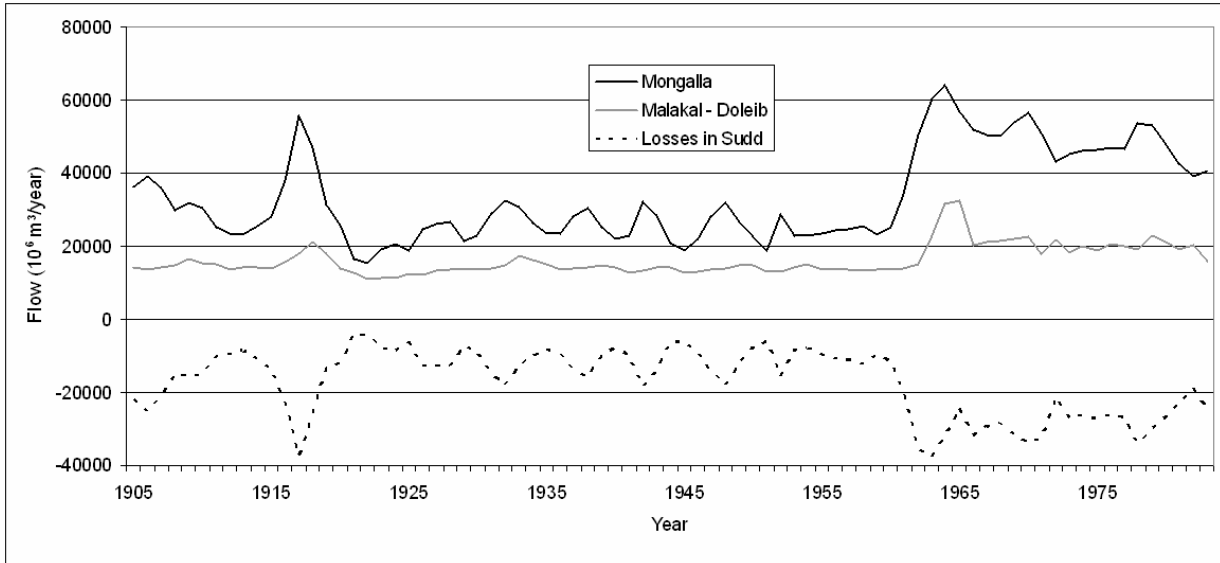


Figure 1.4: Inflow at Mongalla, outflow at Malakal and losses in the Sudd area derived from Hurst (1932 and Supplements). High losses, damping and delay of peaks are visible when comparing Mongalla inflows with outflows at Malakal of which River Sobat inflows at Doleib have been deducted.

The morphology of the area is defined by the channel and lagoon system of the permanent Sudd swamps, the adjacent flood plains and the surrounding flat terrain. The Bahr el Jebel runs to the north-northwest and therefore in an angle to the gradient of the floodplain which is sloping down to the north. While north of Juba the river flows in an incised trough, the banks of this trough decrease in height from south to north with the Bahr el Jebel approaching Bor and end in the Sudd floodplain just north of Bor. In the southern part, the river meanders from side to side in the restraining trough in one or more channels, but further north the swamp is not limited by higher grounds and the system of river channels becomes increasingly complex.

The geology of the area is defined by heavy clay soils, highly impermeable with a top layer of Vertisols of approximately 500 mm depth in average. Sandy soils are found only in depth of 12 to 20 m as shown by drilling profiles of OLS Water, Lokichoggio. The Vertisol top layer cracks deeply during the dry season with the soil recharging up to 350 mm of water during rains. Also soil evaporation and, with the start of vegetation growth, evapotranspiration influences the soil water content significantly. When saturated, the soils get impermeable which indicates a very limited groundwater influence on the area hydrology.

Based on observations, vegetation cover of the area can generally be classified in five categories which occur depending on the elevation above, and distance from the river.

- Swamp
- River flooded grasslands (*toic*)
- Rain flooded grasslands
- Wooded grasslands
- Woodlands

While the permanent swamp is inundated all year round, the river flooded grasslands get inundated with rising water levels and spill from the swamp. Predominantly grassy species, adapted to long term inundation of several months, are found in these areas. Rain flooded grasslands get periodically inundated through accumulating rainfall. Periods of inundation are less than in the river flooded grasslands. Areas that get inundated less frequently show woody species and on higher elevations, dense woodlands can be found. In some areas the vegetation may be altered by human impact through farming or grazing.

The density of the grasslands is changing depending on the season, being tall grass in the rainy season and short and dry in the dry season, where also frequent fires occur. The fluvial area is generally overgrown with vegetation, with some main and side channels as well as lagoons of open water. The vegetation distribution is described in further detail by JIT (1954). The main species are shown in Table 1.1.

Table 1.1: Main vegetation species found in the Sudd area (JIT, 1954)

<i>Phragmites communis</i>	shallow flooded (max 130 cm)	buried roots
<i>Echinochloa pyramidalis</i> (grazing)	shallow flooded (max 130 cm)	buried roots
<i>Oryza barthii</i> (grazing)	shallow flooded (max 130 cm)	buried roots
<i>Echinochloa stagnina</i> (grazing)	deep flooded	superficial/floating roots
<i>Vossia cuspidate</i>	deep flooded	superficial/floating roots
<i>Cyperus papyrus</i>	deep flooded	superficial/floating roots

The first three species shown in Table 1.1 are anchored so their distribution is limited to the depth of flooding, for the last three species their root system needs to be in water or saturated soil permanently which gives a good indicator on flood patterns. *Phragmites communis*, *Echinochloa pyramidalis* and *Oryza barthii* for example dominate only in areas where the depth of flooding does not exceed 130 cm over a period of ten years or 118 cm for a month in the year. Floating vegetation of *Cyperus papyrus* had caused blockages in the Sudd swamps in a number of occasions between 1879 and 1900 when, the plants were torn out by increased floods. From this it can be concluded that *Cyperus papyrus* needs saturated conditions, can tolerate deep flooding, but is limited to a certain range of flooding which appears to be 150 cm (Sutcliffe, 1974). As an invasive species, *Echornia Crassipes* which has not been reported in earlier reports has been found during assessments in the swamps. Typical swamp vegetation is shown in Figure 1.5.



Figure 1.5: Papyrus, reeds and water hyacinth in the main swamp area near Baidit/Padak in April 2004

As the main artificial feature in the area, the Jonglei Canal was planned and partly constructed to divert water from Bor to Malakal, avoiding evaporation losses in the Sudd swamps where currently half of the inflowing water is lost by evaporation. Anyhow this structure is not finalized and does currently not play a role in the Sudd system.

Pastoralists use the Sudd and the surrounding areas extensively. Cattle herding and rainfed agriculture are the dominant means of support for the largely rural population for which the seasonal flooded grasslands along the Sudd provides valuable grazing lands (Baecher, 2000).

1.3 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). Based on an earlier description of the whole Nile Basin (Hurst & Phillips, 1931), a detailed description of the swamps, being the state of the art at that time, was provided. Both authors described meteorological conditions, topography, hydrology and vegetation in the swamps and investigated the losses of half the inflowing waters which evaporate in the swamps. As evapotranspiration was underestimated at that time, the losses could not be sufficiently explained. In the same series of publications, Hurst in 1932 and 1933 published measured time series of water levels and flows for a variety of stations in the Sudd and along the whole of the Nile which were later continued by the Egyptian Ministry of Irrigation as supplements to the initial Nile Basin Volumes. Containing flow as well as water level time series data starting from 1896 to 1982 these records are up to date the most comprehensive source of time series data for the Sudd swamps.

Penman (1948) assessed and established general methods to estimate evaporation in wetland areas. Detailed studies regarding this topic in the Sudd swamps were carried out by Migahid in 1948 and 1952, aiming at improving the understanding of the swamp vegetation and related evapotranspiration losses. Migahid conducted experiments using large tanks filled with papyrus, monitoring evapotranspiration. He achieved realistic results of 2080 mm/year enabling him to better explain the losses in the system.

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 (1957) 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 route 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 to those carried out by JIT (1954) have been conducted by Mefit-Babtie (1983) and Howell *et al.* (1988). While utilizing the existing historical information also new data was collected and data assessments were carried out to reassess the potential impacts and opportunities of the Jonglei Canal using up to date data and knowledge. The studies confirmed that the local subsistence economy depends on the seasonal flooded grasslands provided by the river spill and established the interaction between hydrological factors of flooding and the ecological factors controlling the distribution of vegetation species in the permanent swamp and seasonally flooded areas.

Euroconsult (1981) carried out detailed surveys in the Bor - Mabiior area, carrying out similar assessments to those conducted by JIT (1954) but on a smaller scale focused on the immediate area of interest for which flood protection dikes were planned to be implemented. Topographic surveys, socioeconomic assessments and hydrological studies were conducted resulting in a set of design parameters for the planned dikes but also listing a number of interesting statements including the dramatic and constant changes in the hydrology caused by changing flow regimes, the lack of suitable data and the related uncertainties in predicting the system.

In 1989 the World Bank-UNDP issued the Sub Saharan Hydrologic Assessment report which contains an important account for the available data in the Sudd area including lists of station coordinates. As in the Nile Basin Volumes station locations are only referred to by their distance from Lake No, the report forms an important asset in providing exact station locations for historical gauges. On the hydrological side, Sutcliffe & Parks in 1999 provided an account

of the available process related knowledge for the Sudd, describing flow conditions, the influence of the flat topography, the flood regime and the hydrological control of the floodplain vegetation including vegetation distribution.

Another important aspect related to the swamp vegetation is described by Koponen & Kummu (2004) who described the effects of Sudd blockages in Lake Kyoga. Raised water levels had dislodged papyrus vegetation and water hyacinth mats that fully blocked the outlet of the lake. The study describes the processes leading to blockage as well as the behavior of the blockage itself, concluding that the main effects are raised water levels in the upstream areas, changed outflow patterns and discharge quantities that are reduced by evapotranspiration in the increased upstream water surface areas. Due to the similarity of vegetation and flow regime, the findings can be assumed to be as valid for the Sudd area.

While so far no two dimensional numerical modelling techniques with their advantages of detailed spatial overviews of the hydrologic behavior have been applied for the Sudd, there have been regional as well as large scale routing model studies for the whole Nile basin and its large scale features. Sutcliffe & Parks (1987) developed the above described regional mathematical model using Nile flows at Mongalla and Malakal. Georgakakos & Kohm (1995) aimed to investigate water resources management problems and developed the Nile Decision Support Tool. The model purpose was to assess the benefits and tradeoffs associated with various basin wide water development and management options. Its main components included a database, river simulation and management, agricultural planning, hydrologic modelling, remote sensing, and a user-model interface. The river routing model used in this work represented the losses in the Sudd swamps based on balance equations similar to the ones used by Sutcliffe & Parks (1987).

The latest attempt to set up a numerical model for the Sudd swamps was carried out by Petersen (2006). Based on historical data, a one dimensional model was used to assess flood levels in the swamps under different inflow scenarios. The results, in combination with newly measured water level data, were used to establish design criteria for a dike system in the Bor-Mabior area as well as to assess the potential impact of this dike system on water levels in the upstream and downstream areas.

The most recent studies were conducted by Mohamed *et al.* (2004) and Mohamed (2005) who used remote sensing data to assess climatologic aspects of evapotranspiration in the Sudd swamps. Mohamed *et al.* (2004) investigated the spatial variability of evaporation and moisture storage in the Sudd swamps using remote sensing techniques. The Surface Energy Balance Algorithm for Land (SEBAL), a parameterization scheme of surface heat fluxes based on spectral satellite measurements, was used to derive the energy balance components from National Oceanic Atmospheric Administration – Advanced Very High Resolution Radiometer (NOAA-AVHRR) images of the swamps. With this technique, the actual evaporation and soil moisture of the Sudd region have been investigated and verified against long term averaged rainfall and flow data. Results show evaporation being controlled by soil moisture availability and the wetland area to be significantly larger than previously assumed. As the studies investigated actual evaporation over the Sudd region including the periodically dried out seasonal floodplains, the results of 1636 mm/year are substantially less than for example the

2150 mm/year proposed by Sutcliffe & Parks (1999) who based his assessments on water balance equations for the permanent swamp.

Mohamed (2005) expanded on the assessment of actual evaporation and moisture storage aspects and analyzed moisture recycling processes in the Sudd swamps including the potential impacts of draining the Sudd wetlands on the local and regional hydroclimatology. Regional climate modeling was used as the basic tool for the investigation. Results of this study indicate that in general the Sudd has a negligible impact on the regional hydroclimatological budget as the amount of moisture recycling by the swamp is small compared to the atmospheric fluxes over the region. Draining the swamp and bypassing water would therefore only be of concern for the microclimate in the swamps themselves where the impact would be large. The study estimates that within the swamp the near surface relative humidity would drop by 30 to 40% during the dry season and that the temperature would rise by 4 to 6 °C. The impact during the wet season was judged as comparatively small.

1.4 Field work

Field work has been carried out in the swamps over a three year period between 2004 and 2006 covering three flood seasons to supplement and expand the partly scarce historical data sets, to obtain information on a variety of interlinked parameters and to investigate problems like evapotranspiration and soil water recharge in great detail in a defined area of interest between Bor and Shambe. While initially few monitoring stations were set up measuring water levels and rain in a pilot area only (Baidit/Padak), in early 2005 the station network was expanded covering the full area between Bor and Shambe with electronic monitoring stations measuring water level, rain, wind speed, sunshine, humidity and temperature in daily timesteps as described in more detail in Chapter 4.

In addition to the stationary measurements, experiments have been conducted measuring flow velocities and bathymetries in the swamp as well as evapotranspiration, soil evaporation and soil water recharge on the floodplains, the experiments are described in detail in Chapter 4. Also living in the area and monitoring the swamps and floodplains through daily observation of changes by eye and noting these were important for a thorough understanding of the vast system.

1.5 Scope, structure and objectives of this study

The Sudd region has, for long periods of time, been inaccessible due to civil wars in southern Sudan. While studies have been carried out using remote sensing products (Mohamed, 2005), on-ground data have not been available since the old stations, set up by the Egyptian Ministry for Irrigation had been abandoned or destroyed, the last ones in 1983. Development works carried out in the area offered the opportunity to link a hydrological study to these activities to assess the hydrologic and hydrodynamic processes in the area. The generated information will be most important for any future development, be it for homestead security, irrigation, transport, fisheries or any other activities linked to the waters of the swamp.

The study, encompassing the area between Mongalla and Shambe with a core area of interest between Bor and Mabior, has aimed to evaluate the water balance and hydrodynamics in the system including local and external driving factors ranging from the significance of the inflows from the great lakes to local rainfall and evapotranspiration. It has generated an in depth understanding of the hydrodynamics of the system and the processes controlling the yearly flooding and drying cycle.

Specific objectives include the establishment of a sound area description and hydrological database, followed by an assessment of the area morphology, vegetation dynamics, water balance and runoff. They also include the setup of a calibrated and validated DHI MIKE21 2D numerical hydrodynamic model to assess the hydrodynamic conditions within the permanent swamp and on the seasonal floodplains based on the outcome of the data analysis and model simulations.

Chapter II - Morphological analysis of the Sudd region using land survey and remote sensing data

G. Petersen, J.V. Sutcliffe and N. Fohrer
Earth Surface Processes and Landforms 33 (2008)
Submitted: 23.11.06, Accepted 01.11.07, Published 13.05.08

Abstract

An analysis of the vast wetland of the Sudd swamps in southern Sudan was designed to assess and describe interdependencies between morphology and hydrology. Findings based on field survey and remote sensing data include an assessment of the effect of ground slopes and morphological features on spill and flooding of the seasonally flooded grasslands. Through bathymetric surveys and analysis of Landsat images, depth profiles and cross sectional depth and flow distributions were established. Data from remote sensing, field survey and historical sources were correlated and correction factors established; the SRTM was partly found unsuitable for further assessments. Further analysis of remote sensing data was used to investigate the Sudd's inland delta as well as the question of spill into the Bahr el Ghazal basin.

Keywords: Bahr el Jebel; Bahr el Ghazal; swamp; Nile wetland; inland delta; SRTM

2.1 Introduction

The Nile swamps of southern Sudan, called the Sudd, one of the largest wetlands in Africa (Mohamed, 2005), have for years been the subject of investigations, without the system being fully understood to date. Many studies were carried out during the first half of the last century for example by Hurst (1932, 1933), and Hurst and Phillips (1931, 1938), who collected a great amount of basic hydrological data in the Nile Basin Volumes which were later supplemented with additional data. More data were collected by the Jonglei Investigation Team JIT (1954) who described the topography and morphology of the Bahr el Jebel similarly to Hurst and Phillips (1938) and Sutcliffe (1974), who had been part of the Jonglei Investigation Team in 1950-1954. Here the river morphology between Nimule and Malakal is described in detail based on river surveys highlighting the decreasing slope and the increasing width of the permanent swamp and floodplain area from south to north. The transition from the defined and fast flowing incised river to a multiple channel inland delta, with river levels above the surrounding floodplains is also described. More information was provided by Sutcliffe and Parks (1999), who re-evaluated the available information at that time, focusing on changes in swamp extent and swamp vegetation after the 1964 rise in Lake Victoria levels and outflow.

During recent years, the Sudd area was largely inaccessible due to civil war and studies relied on remote sensing data. For example Mohamed *et al.* (2004) worked on hydroclimatological

modelling of the region based on National Oceanic Atmospheric Administration – Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellite images.

With peace returned to southern Sudan, the area is now becoming accessible again, and plans for development projects and visions of agricultural potential have generated the need for further and detailed investigations. As modern data are scarce and knowledge of interdependencies sketchy, new basic studies are needed to provide scientific information on the unique Sudd ecosystem, and for future planning and development in the area combining ground survey and remote sensing data.

Being dominated by flooding, any sustainable development in the Sudd will depend on the knowledge of hydrological conditions; these in turn will largely depend on morphological features of the area. An assessment of these, based on new ground survey data acquired in the first stages of accessibility in combination with remote sensing products and available historical data is the main objective of this paper, aiming on enhancing the understanding of the Sudd in regard to the influence and interaction of morphology and hydrology.

2.2 Materials and methods

2.2.1 The study site

The Sudd region, as shown in Figure 2.1, is defined by the Nile, here called Bahr el Jebel. While the study was carried out within the framework of the whole Sudd area between Mongalla and Malakal, ground surveys were restricted to the area between Bor and Shambe due to logistic restrictions. This area marks a transition from the river flowing between restraining banks in an incised trough to the flat unlimited floodplain area in which the river forms its inland delta with meandering multiple channels and lagoons, with wide permanent swamps and seasonally flooded areas. The channel system is constantly changing due to sedimentation, erosion and blockages by floating vegetation, leading to a highly dynamic system.

The Bahr el Jebel, in relation to the Sudd, can basically be divided into five characteristic stretches:

The rapid runoff zone between Nimule and Juba plays an important role in receiving the base flow supply from the equatorial lakes as well as the discharge of seasonal torrents during the rainy season with varying sediment loads (JIT, 1954). An average slope of 1.0 m/km is typical for this reach (Hurst and Phillips, 1938). The flow rates are of major importance for erosion and deposition rates as well as flood levels with respective overbank flow and consequent area flooding in the areas further downstream.

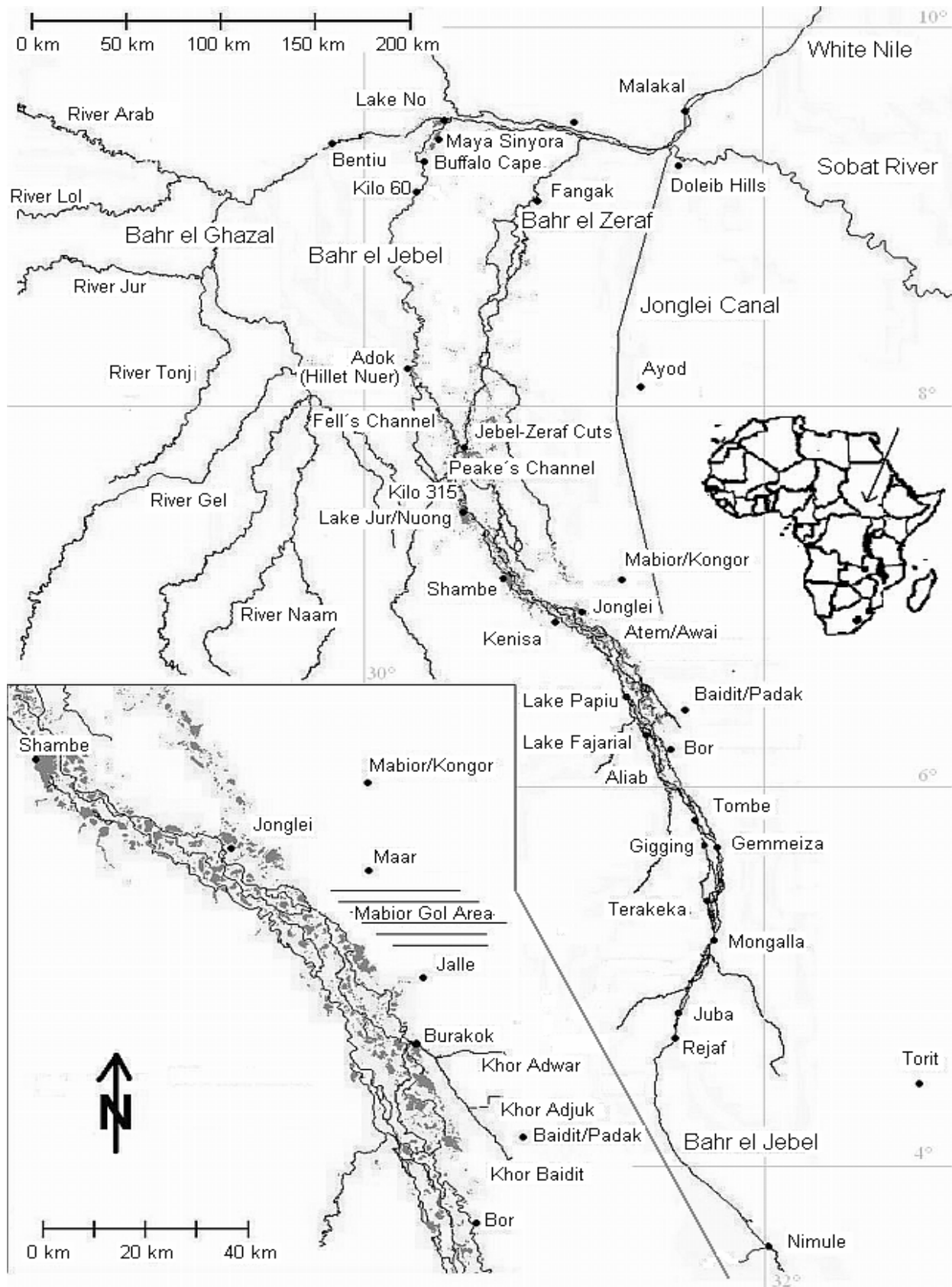


Figure 2.1: Overview of project area in southern Sudan with detailed core area of interest

The defined valley floodplains develop between Juba and Bor where the incised river widens and the Bahr el Jebel starts meandering and splitting up within a constraining trough. Sutcliffe (1974) describes the meandering river forming alluvial banks which are higher than the surrounding floodplains, dividing these into isolated basins which receive spill from, and drain back into the river depending on flood levels.

Between Bor and Shambe the river enters an inland delta with an area of unrestricted flooding marked by multiple channels and lagoons. Within the southern part of this stretch, the incised trough gradually disappears until north of Bor the flooding is unrestricted. During the flood season large areas are inundated through spill (JIT, 1954). Sutcliffe (1974) notes another detail of the area morphology: North of Bor the river is flowing in a direction oblique to the slope of the plain in a north-north-westerly direction. An important feature, the Bahr el Zeraf, branches off from the Bahr el Jebel at an angle to the east. The ground levels in this area show an average slope of 0.1 m/km in a northerly direction. As an important but non functional feature, the Jonglei Canal, an artificial channel built to bypass the Sudd to the east from Jonglei to the mouth of the Sobat terminates in this area. The canal was not completed and has only local influence.

From Shambe to Lake No, the northern swamps are marked by wide papyrus fields, lagoons and meandering and sudded (blocked) channels. This area is described by Butcher (1938) who reports the ground levels in a transect dropping away fairly steeply from the river to about 1.5 m below the river bank level within 1 km. Where subsidiary channels are crossed, the ground levels tend to rise and the whole formation can be described as deltaic.

Finally, after Lake No where the Bahr el Ghazal joins the system and towards the confluence with the River Sobat, the now so called White Nile enters a collecting zone. Here the river bed becomes more defined and confined by relatively high banks (JIT, 1954). The Bahr el Zeraf and finally the River Sobat join the river and the White Nile leaves the swamps at Malakal to the north.

2.2.2 Field assessment methods

Field data were collected as part of the South Sudan Road and Dike Rehabilitation Project, SSRDRP which incorporated a hydrological study for an environmental impact assessment (Petersen, 2006 and Hassan *et al.*, 2006). Field investigations were conducted between 2004 and 2006 in the area between Bor and Shambe by air, river and land. Surveys were carried out continuously or conducted specifically for individual projects. For instance, selected areas were observed monthly to record seasonal changes in flooding and drying, vegetation and soil conditions.

Collection of meteorological data and water levels started in 2004 at a limited number of sites on the Khors Baidit and Adwar (khors are depressions leading inland from the swamps, playing a role in the flooding mechanism of the seasonal flooded grasslands). By 2005 a network of 15 hydro-meteorological Campbell monitoring stations equipped with different sensors was set up. These observed water level, precipitation, wind speed, sunshine, humidity and temperature data and were set up in the swamps and in the surrounding seasonal floodplains between Bor and Shambe, logging data at 2 to 12 hourly intervals.

To investigate the role of khors, three water level gauges were set up at Burakok, Baidit and Adwar (Figure 2.1). Burakok station is located where the khors are connected to the permanent swamp area, Baidit and Adwar station within the khors, towards their tails at the end of the permanent swamp. There was a difference between the khors; a road dam constructed between Baidit/Padak and Jalle had cut off the tail of Khor Adwar. Khor Baidit is undisturbed and connected to its catchment (Figure 2.2).

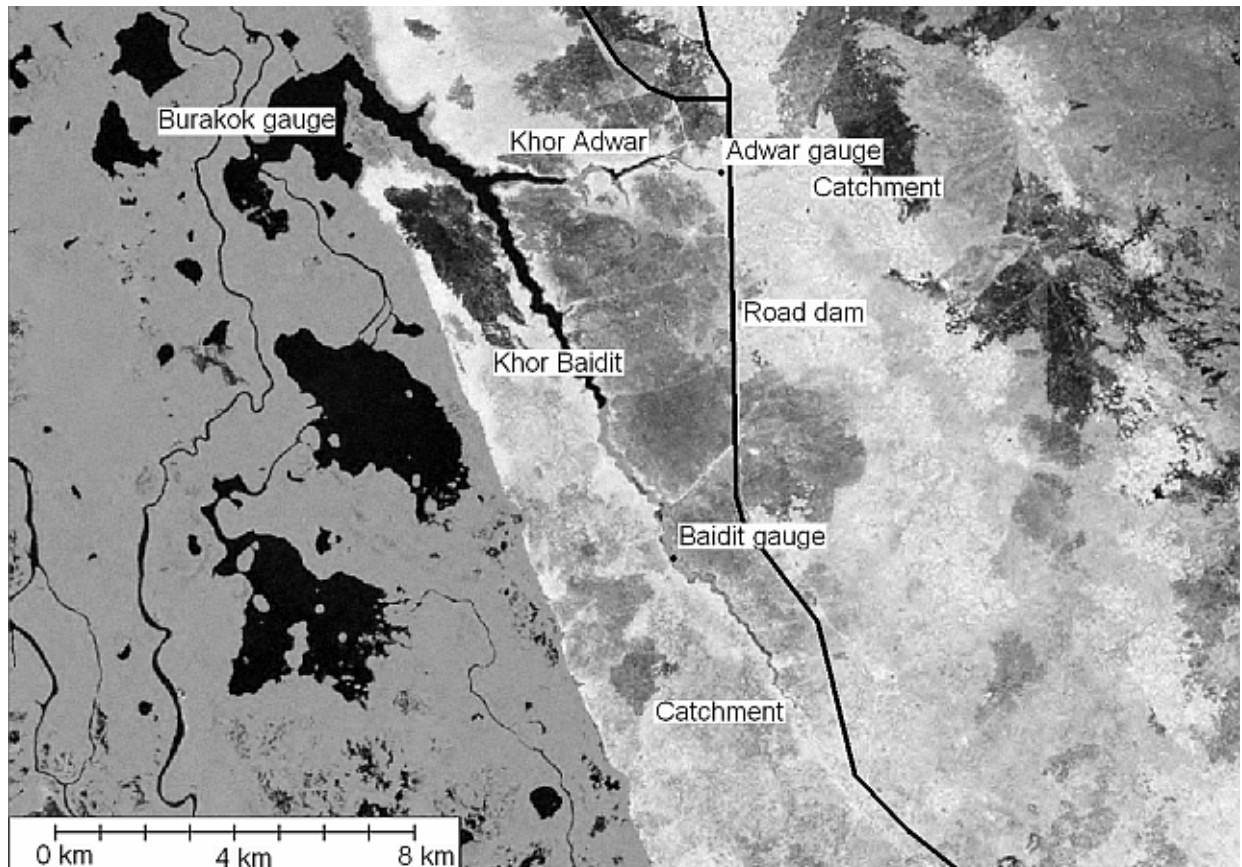


Figure 2.2: Layout of Khor Baidit and Adwar

Land surveys were carried out using optical levels as well as Trimble Differential GPS equipment using the Base-Rover method (Trimble Ltd, 2007) to achieve a relative accuracy of 20 mm within the system.

Bathymetric data of the main river channels were collected between Bor and Shambe during a June 2005 field campaign using a Hummingbird Matrix echo sounding device with GPS tracking facility and data logging ability from small boats (Petersen, 2006). On the 80 km stretch of the Bahr el Jebel main channel, 26,000 sounding points were collected. For measurements within the swamp vegetation, the dipstick method was used.

Current velocities in the main channels were measured with a Seba Mini Current Meter M1 with 50/250 propeller at a depth of 1.2 m in the centre of the channel at monthly intervals between May and November 2005. Measurements within the vegetated areas were carried out using surface floats.

2.2.3 Data analysis methods

Data analysis was carried out for the establishment of ground control points. Specific points of the collected land survey data were referred to matching points of the available historical land survey data by Euroconsult (1981) from which a correction factor between DGPS levels and the historical New Khartoum Level (NKL) was established.

On the remote sensing side, a 1999 SRTM (Shuttle Radar Topographic Mission) DEM with 90 m resolution (NASA, 2006a) has been used to assess the area morphology. This allowed for a good general overview as well as assessing specific details and comparing the results with historical findings. The SRTM data were evaluated for accuracy by Rodriguez *et al.* (2005) and vertical errors were found to be in the range of 0-3 m random error and 3-4 m absolute error for the Sudd region.

Landsat MSS (Multi Spectral Scanner) satellite images (NASA, 2006b) of the dry and wet season of 1979 (February and October) have been used to measure the cross sectional vegetation, lagoon and channel distribution in the swamps between Bor and Shambe. For the delineation, visual interpretation from Landsat band 1/2/3 false colour composites has been used, which showed the best approximation of the boundary between water and vegetation. The method is further described by Petersen *et al.* (2007).

2.3 Results

2.3.1 Morphological features

As described in Section 2.2.2, land survey was largely confined to the area between Baidit/Padak and Mabior, while river surveys were conducted in the larger area between Bor and Shambe. Results in this section focus on this area but are also relevant for areas further upstream and downstream in the Sudd where conditions are similar.

The first finding of the ground survey was the establishment of a general northward slope of 0.1 m/km. Surveys also established control points to relate the local Differential GPS derived levels with the historical New Khartoum Levels (NKL). The correction factor between NKL used by Euroconsult and the DGPS readings was calculated as 8.8 m, the DGPS readings being higher than the NKL values (Petersen, 2006). The comparison is shown in Table 2.1.

Detailed surveys were carried out in the Mabior Gol region and around the Khors Baidit, Adwar and Adjuk to investigate the flooding mechanism (Petersen, 2006). The Mabior Gol, a major wetland, has not been described previously. It is likely that the flooding of this wetland area, which is slightly below the surrounding ground, is related to changes in the flooding regime, and now marks the boundary on the eastern bank of the river valley where the incised trough as described in Section 2.2.1 disappears. The area can clearly be distinguished from early dry season satellite images of 1979; the location is indicated in Figure 2.1.

Early evidence on the surveyed khors was found in the available literature, dating back to the beginning of the 20th century. PJTC (1977) described the role of the khors as playing a role in

carrying floodwater inland and draining rainfall runoff towards the swamps. From regular observations in 2005 (Petersen, 2006), the khors role in drainage and flooding of the area was assessed at the Khors Adwar and Baidit. The western and eastern sides of Khor Adwar, cut by a road dam, were observed independently. The western side was connected to the swamps; the tail on the eastern side was cut off but connected to the upper catchment. While on the western side the water levels rose and fell with water levels in the swamps as shown in Figure 2.3, the eastern side, now cut off, showed little water accumulating despite typical rainfall events.

Table 2.1: Levels used for comparison of Euroconsult NKL values; DGPS measurements and SRTM DEM extracted levels from which correction factors were deduced in the area between Baidit/Padak and Mabior. Locations are given as road and dike chainages from Baidit/Padak to the north

Location	NKL (m)	DGPS (m)	$\Delta_{\text{NKL-DGPS}}$ (m)	SRTM (m)	$\Delta_{\text{NKL-SRTM}}$ (m)
8+000	418.66	427.48	8.82	423.0	4.34
9+400	418.59	427.34	8.75	423.0	4.41
10+400	418.38	427.35	8.97	423.0	4.62
12+500	418.18	426.65	8.47	423.8	5.62
16+000	418.05	426.86	8.81	422.5	4.45
18+300	417.87	426.38	8.51	422.5	4.63
20+100	417.61	426.42	8.81	422.0	4.39
22+600	417.33	426.19	8.86	423.5	6.17
25+600	417.04	425.83	8.79	422.0	4.96
27+700	416.76	425.91	9.15	420.8	4.04
Maar	414.34	423.14	8.80	418.0	3.66
Paliau	413.12	421.57	8.45		
Mabior	411.36	419.95	8.59		
Average			8.75		4.66

Compared with the surrounding slightly higher ground around the khor, observations showed that soil cracks were closing earlier and the grassier and less bushy vegetation was more luxuriant within the khor, indicating wetter soil conditions. Similar observations were made further north in regions normally flooded, but now protected by newly constructed dikes. While rainfall was typical, no area flooding occurred behind the dikes. As a second trial, water levels collected at three stations at Burakok, Khor Adwar and Khor Baidit were compared. Water level fluctuations at these stations, all connected to the swamps, show a similar pattern but differ in elevation (Figure 2.3).

2.3.2 River bathymetry

Measured water depths in the Bahr el Jebel between Bor and Shambe have been analyzed. In the main channels, depths typically between 3.7 and 8.5 m with an average depth of 6.1 m were found as shown in Figure 2.4. Lagoon depths vary between approximately 2 to 4 m and water depths within the papyrus swamps averaged between 0.1 and 1.2 m with a mean depth of 0.4 m, disregarding the channel boundaries.

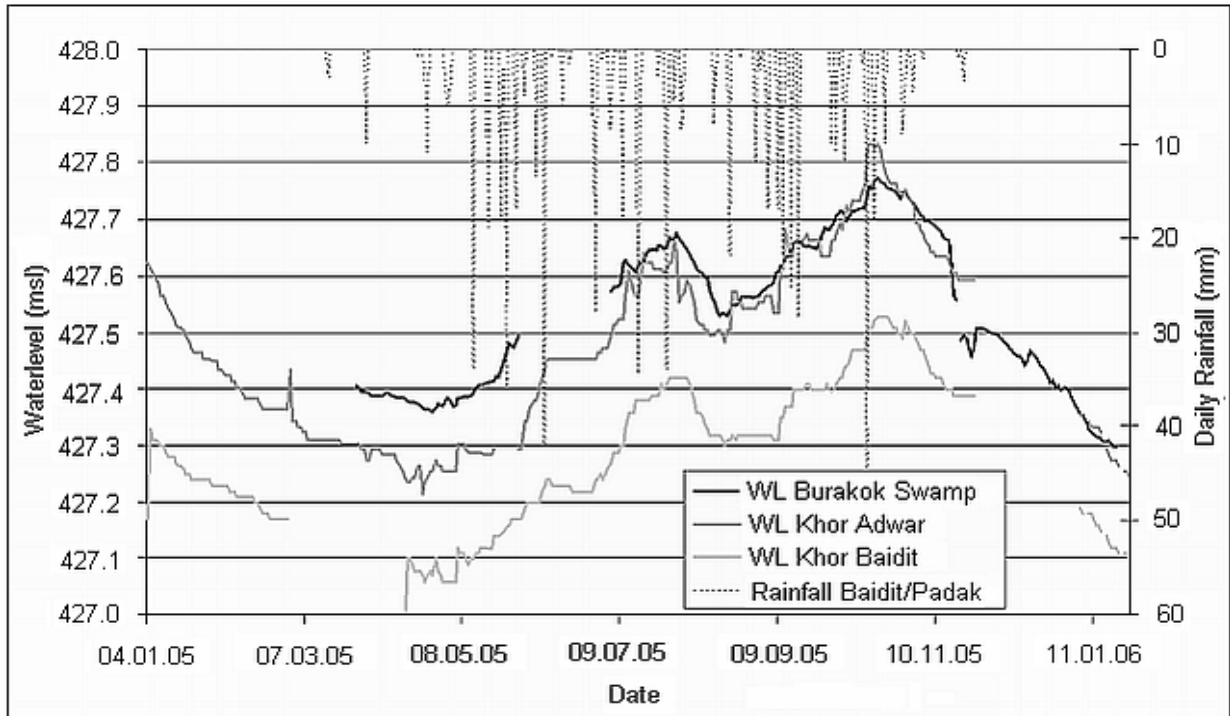


Figure 2.3: Water level (WL) time series of Burakok (within the Swamp) and at the tails of Khor Adwar and Khor Baidit showing surface level fluctuations in correlation to the wet and dry season. (Note that the station at Khor Adwar is not cut off but located just to the west of the road dam)

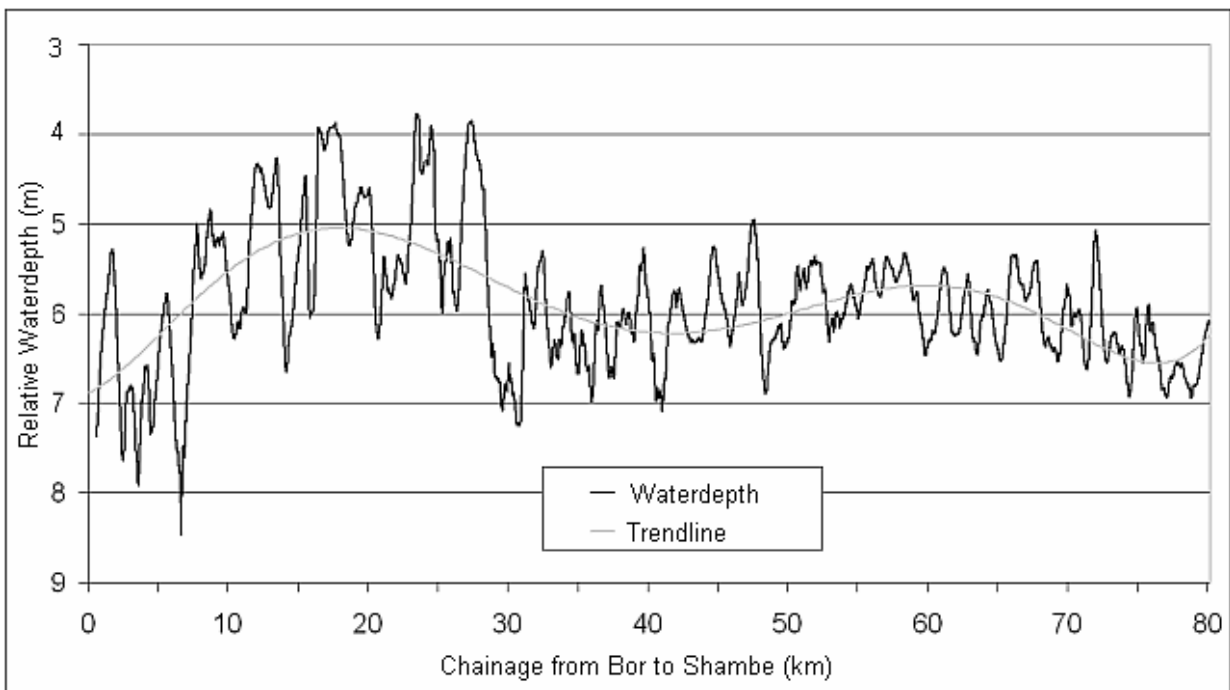


Figure 2.4: Depth profile along Bahr el Jebel main channel from south to north between Bor and Shambe. In the upstream part the depths are variable, but less so further downstream after chainage 30 km. The trend line shows an interpolated moving average of the depth

It was noted during the surveys that at the channel and lagoon boundaries, floating vegetation spread into the channel water body; this leads to underestimation when estimating open water width from remote sensing or echo sounding data. Vegetation growth along channel boundaries has been described in detail by Migahid (1948). As well as the bathymetry readings current velocities were recorded. Velocities were measured as 0.470 m/s average for the main channels and 0.003 m/s average within the papyrus swamps. The flows within the papyrus were highly variable at different sites and varied between 0.0 and 0.1 m/s with the zero and lower velocities dominating. The findings are similar to those of Hurst and Phillips (1938) who estimated average flow velocities of 0.001 m/s within the papyrus swamps. These depths and velocities were used to estimate the proportion of flow outside the main channels.

2.3.3 Morphological analysis from SRTM Digital Elevation Model (DEM)

Evaluating the DEM in Figure 2.5 and Figure 2.6 on a coarse scale, varying slope directions can be identified along the course of the Bahr el Jebel. From Bor northwards, where the incised and restricting trough disappears in the east, the ground slopes in a north-northwesterly direction, like the flow direction of the river. After reaching Shambe, the ground-slope changes into a westerly direction towards the Bahr el Ghazal basin, while the river, bound by alluvial banks, is heading oblique to this slope towards the north until it reaches Lake No. Slope gradients can be estimated as 0.1 m/km, with very limited local undulations, the only pronounced features being the incised river trough south of Bor with banks disappearing further north. The system changes to another formation visible from the DEM, the pronounced inland delta between Baidit/Padak and Shambe as shown in Figure 2.5. Here the channel flows at higher elevation than the surrounding plains, with level differences between the river and the surrounding plains about 2-3 m. Further north the inland delta becomes less defined, but can still be observed running obliquely to the general westerly slope of the area towards the north. A series of cross sections derived from the DEM at locations perpendicular to the river are shown in Figure 2.7, illustrating the transition from incised trough to elevated inland delta.

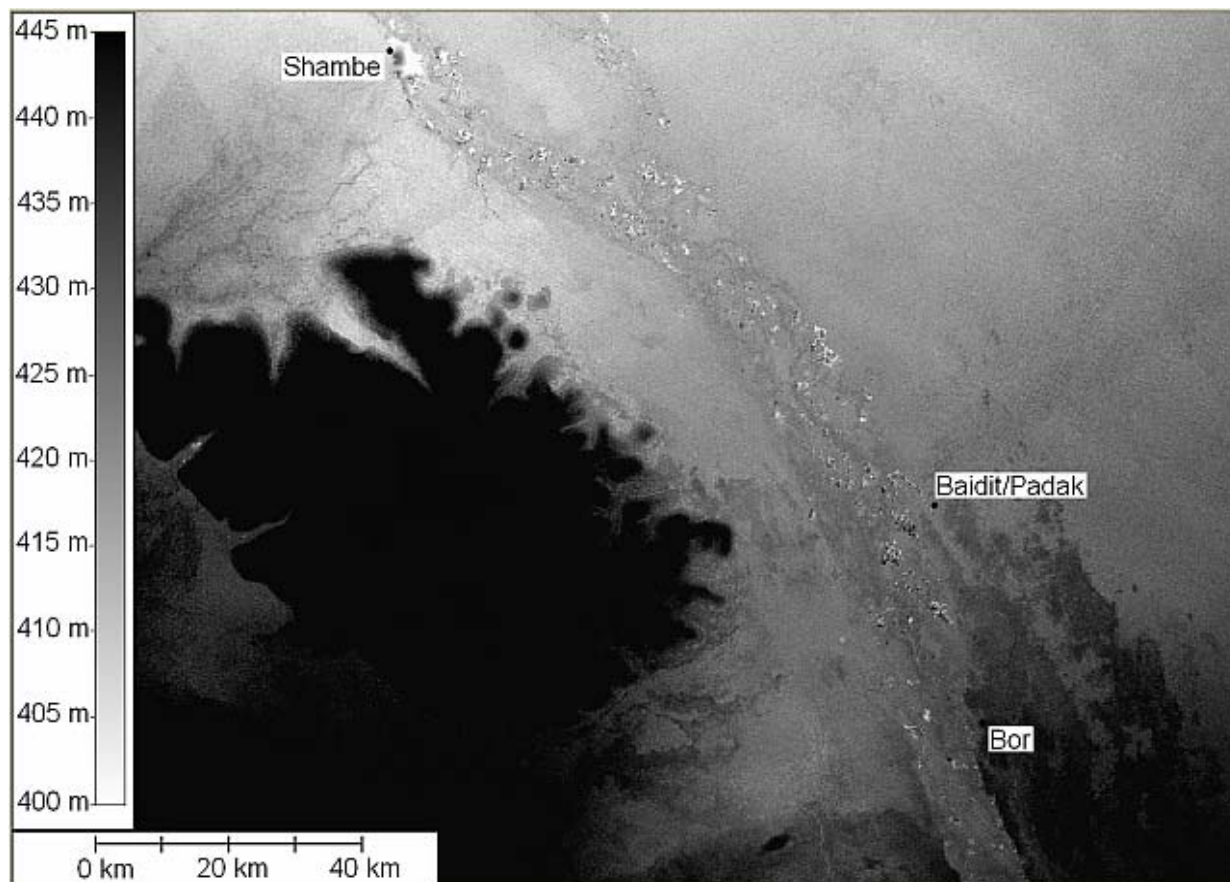


Figure 2.5: SRTM DEM of the area between Bor and Shambe showing an inland delta formation. The transition from incised trough in the south to elevated channels in the north is clearly visible

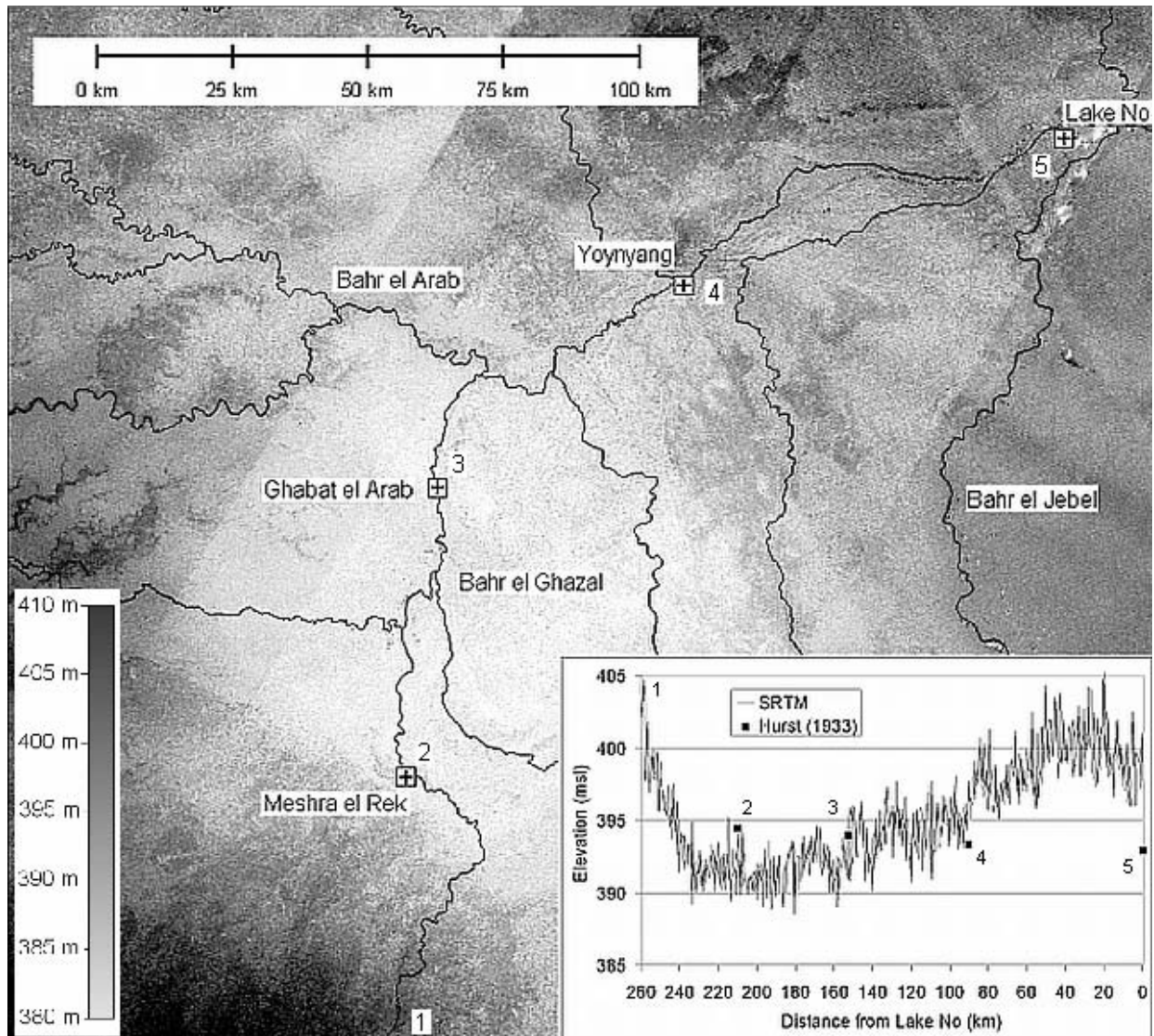


Figure 2.6: Comparison of SRTM DEM and land survey elevation. The depression in the DEM data is clearly visible both on the map (light area) as well as in the graph, representing levels along the course of the Bahr el Ghazal from upstream Meshra el Rek (1) to Lake No (5). The land survey elevations for the stations Meshra el Rek, Ghabat el Arab, Yoinyang (near Bentiu) and Lake No are deduced from data collected by Hurst (1933), corrected to NKL + 6.8 m and show the discrepancy from the DEM data

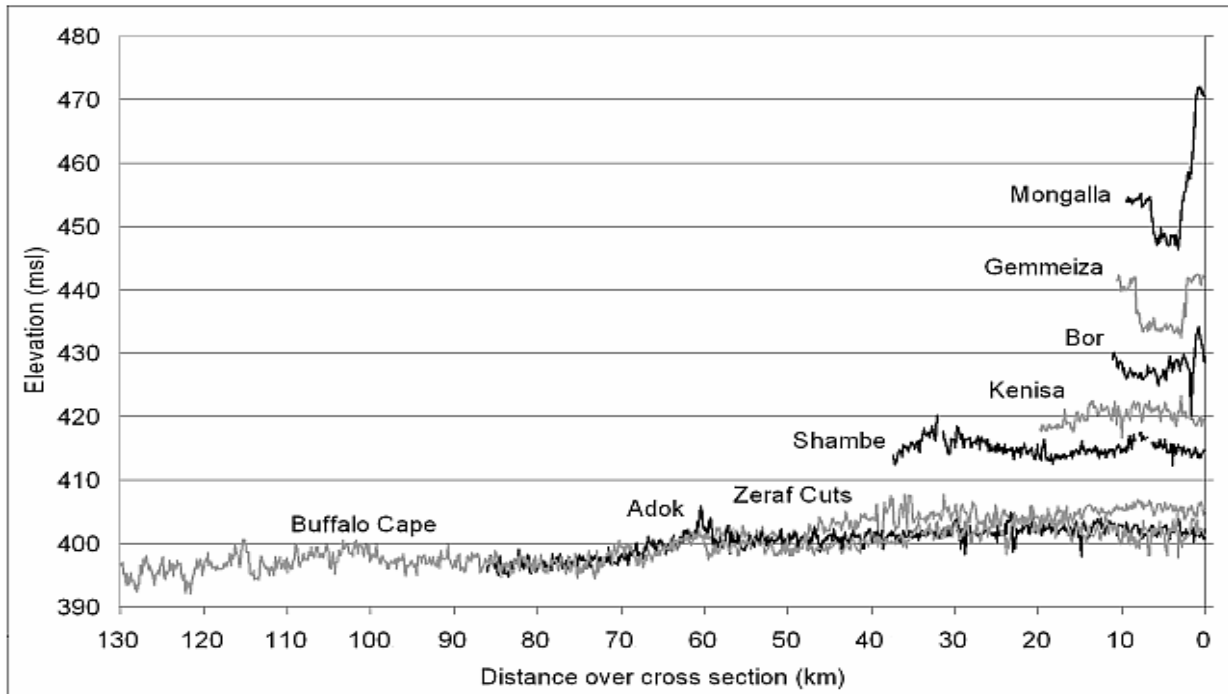


Figure 2.7: Series of cross sections between Mongalla and Buffalo Cape near Lake No extracted from SRTM DEM. The sections are taken looking downstream showing the transition from incised trough to elevated deltaic formation as well as the slope towards the Bahr el Ghazal basin in the northern (lower) areas

Cross sections from JIT (1954) have been digitized and compared with SRTM DEM extracted cross sections as shown in Figure 2.8. While qualitatively the cross sections are very similar, the absolute values vary. A general discrepancy of approximately 6.8 m is observed between the SRTM DEM and the JIT (1954) sections which are based on the old Khartoum benchmark level estimate of 360.0 m.

Detailed comparisons of specific DEM extracted values for locations where NKL values are available from Euroconsult (1981) show an average correction factor of 4.7 m, the SRTM DEM showing higher elevation values than the NKL levels as shown in Table 2.1. For the northern area of the swamps, DEM analysis indicates that apart from some natural ground undulations, a continuous slope from the Bahr el Jebel towards the Ghazal basin exists. Gradients have been estimated as 0.1 m/km in a westerly direction from JIT (1954) cross sections as well as SRTM DEM data. A finding made during the SRTM DEM evaluation is a depression shown in the digital data in the lower Bahr el Ghazal basin, southeast of Bentiu as shown in Figure 2.6. The area is indicated as swamp on topographical maps. Quantifying the elevation difference, the floor of the depression at its centre is 8.0 m lower than Lake No. The distance is approximately 150 km.

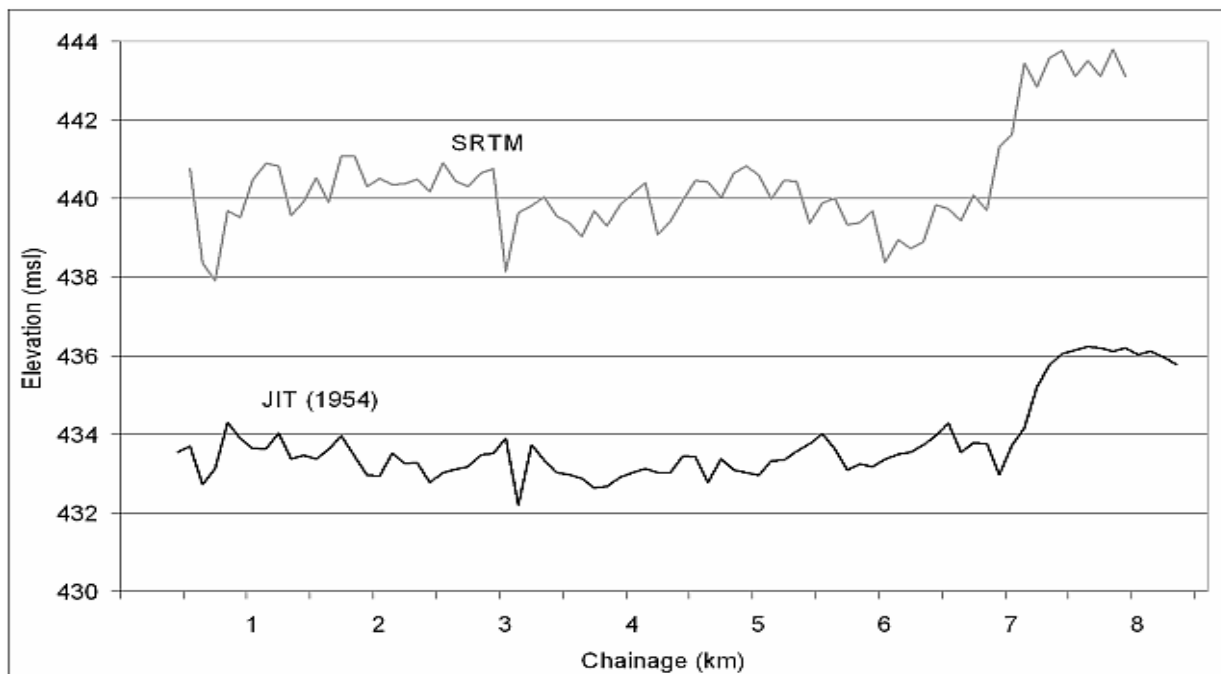


Figure 2.8: Comparison of JIT (1954) and SRTM derived cross sections 2 km upstream of Terakeka

2.3.4 Evaluation of Landsat satellite images

Evaluation of Landsat images has been used to estimate the possible importance of water flows through swamp vegetation. Flood plain cross sections between Bor and Shambe were analyzed in terms of proportions of swamp, lagoons, open channels and seasonal flooded grassland, locally named *Toic*. Results show the percentage of swamp cross section increasing from south to north. Details are shown in Table 2.2.

Another persisting problem in the region between the Bahr el Ghazal and Bahr el Jebel is the watershed delineation between the two catchments (Mohamed, 2005). Historically Hurst and Phillips (1938) as well as Butcher (1938), JIT (1954) and also Howell *et al.* (1988) considered spill from the Jebel into the Ghazal basin as a possible cause of water losses from the Sudd. Visual interpretation of Landsat satellite images does not show any evidence of delineation, with consistent swamps between Shambe and Lake No. This last finding, as well as the SRTM derived slope, supports the possibility of spill as described in Section 2.3.3.

Table 2.2: Percentage distribution of swamp type over different cross sections

Cross Section %	Bor	Baidit	Adwar	Jalle	Maar	Shambe	Average
Swamp	71	86	68	79	88	86	80
Lagoon	25	11	29	18	10	12	18
Channel	4	3	3	3	2	2	2
<i>Toic</i> (% in relation to permanent swamp)	0	0	30	37	69	62	-

2.4 Discussion

2.4.1 Interaction of morphology and hydrology

With regard to the Sudd morphology, the function of khors and their influence on draining and flooding of the seasonal floodplains has been assessed from three sample sites. In the very flat seasonally flooded grasslands, these slight depressions are the only natural morphological features. From the results presented in Section 2.3.1 it can be deduced that the khors' role in rainfall runoff is negligible under normal rainfall conditions, while their role in carrying floodwaters inland is significant. The definition of their catchment or drainage area is very difficult if not impossible, as the low surface gradient, apart from the extreme rainfall which might cause creeping flow, does not allow for significant flow.

Another indication of the function and general flow direction of the khors can be deduced from water level difference between the upper and lower end of these features as shown in Figure 2.3. While all water levels fluctuate in accordance with the seasons, differences in level as well as in reaction are obvious. A moving average of the water level at Burakok is, despite heavy rainfalls, permanently higher than the levels within both Khor Adwar and Khor Baidit, indicating flows towards the tails but not towards the swamps. In addition, comparison of water level fluctuations recorded by the Adwar and Baidit stations give evidence of the negligible importance for draining rainfall runoff. While at Khor Adwar the upper catchment is cut off by the road dam as described in Section 2.3.1, it is functional at Khor Baidit. The time series for the two stations shown in Figure 2.3 are very similar despite the different upstream conditions, indicating no visible influence of the upstream catchment.

The observations made further north in regions normally flooded, but now protected by newly constructed dikes, confirmed the above assessment that floodwaters from the rivers are the main cause of area flooding while pure rain just leads to the closure of soil cracks but no area flooding except in cases of severe rainfall which might lead to standing water and creeping flow. Observations in the Mabior Gol area between Jalle and Maar showed that overland flooding caused by rising floodwaters in the swamps occurs even without the presence of khors. These flood waters moving far inland are an important feature of area flooding.

2.4.2 Cross sectional depth and flow distribution

The influence of distribution of channels, lagoons and papyrus swamp areas within the permanent swamp was assessed using findings from bathymetry and Landsat analysis as described in Sections 2.3.2 and 2.3.4. An analysis of randomly selected cross sections based on Landsat images shows the width distribution between channels, lagoons and swamp as 2 %, 18 % and 80 % respectively as shown in Table 2.2. Using the depth and velocities established during the surveys, a flow cross sectional distribution as shown in Table 2.3 can be estimated. These calculations show that channels carry 93 % of the flow, while only 7 % is carried within the swamp and lagoon cross section. Previous assumptions that a considerable flow might be carried within the papyrus swamps outside the main channels can therefore be discounted. As a consequence, historical flow data collected at main channel locations within the swamps might be representative for the flow at the respective latitude when applying a correction factor which can be deduced from the above percentages.

Table 2.3: Cross sectional flow analysis averaged over the different measured cross sections between Bor and Shambe

	Width (m)	Depth (m)	A (m ²)	v (m/s)	Q (m ³ /s)	Q (%)
Channel	475	6.1	2898	0.470	1362	92.6
Swamp	15117	0.4	6047	0.003	18	1.2
Lagoon	3025	3.0	9075	0.010	91	6.2

2.4.3 SRTM analysis

SRTM DEM extracted elevations were compared against historical land survey data as described in Section 2.3.3. Taking account of the established correction factor of 6.8 m (considering the JIT (1954) comparison as more accurate as based on more points), the data were found suitable for providing further qualitative cross sectional data while it has to be noted, that due to accessibility restrictions, only data from the Baidit/Padak region were used for the establishment of this correction factor.

Quantitative analysis of the data shows that over short distances and in fine resolution levels vary quite significantly and the data would not provide correct information for that level of detail. In this case the possible absolute and random errors as described in Section 2.2.3 would be of great influence and need to be taken into account. An example of the compared cross sections is shown in Figure 2.8. At the same time the SRTM DEM was used for a qualitative larger scale assessment of the Sudd area. The SRTM as shown in Figure 2.5 clearly shows an inland delta forming on the plains at the exit of the incised trough. In Figure 2.6, the continuous slope from the Bahr el Jebel towards the Ghazal basin is shown, supporting the spill theory first proposed by Butcher (1938).

Evidence of spill under certain high runoff conditions through the western plains north of Shambe was discussed by JIT (1954). These findings were confirmed by close evaluation of SRTM DEM data, from which a general slope from the Bahr el Jebel swamps in a westerly direction with an average gradient of 0.1 m/km could be determined. However, flow into the Bahr el Ghazal basin would not be possible with this slope, given the vegetation and evapotranspiration conditions, even under high runoff conditions gradients over the long distance will not change significantly. It can be assumed that under conditions where water spills over the riverbanks, significant quantities of water flow towards the west but are evaporated before reaching the Ghazal.

The slope, as well as the depression within the Bahr el Ghazal basin as described in Section 2.3.3 was assessed carefully. Considering a possible error in the DEM, the data was compared to error analysis from Rodriguez *et al.* (2005). Results show that the observed level differences are twice the possible error. This in combination with the homogenous appearance of the depression and confirmation of its existence from an ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (NASA, 2004) stereo image derived DEM (Petersen, 2006), leads to a confirmation of its presence based on remote sensing resources.

Comparing this finding to field survey data collected during measuring campaigns by JIT (1954) shows a different picture. Evaluation of survey transects show continuous slopes towards Lake No. The same slopes can be deduced when comparing water levels at different

gauging stations along the river based on data from the Nile Basin Volumes (Hurst, 1933 and supplements). A comparison of the levels is shown in Figure 2.6. Evaluation of flow data from these stations confirms the existence of these slopes by indicating that most of the contribution to the Bahr el Ghazal discharge at Lake No originates from the upstream tributaries. The contribution was deduced by subtracting the gauged Bahr el Arab discharge from the discharge of the Bahr el Ghazal at Lake No for 1957, a year for which full data coverage was available. While the discharge at Lake No was 500 million m³/year the Bahr el Arab contributed 10 million m³/year. The remaining 490 million m³/year must therefore originate from upstream tributaries.

In consequence the field data does not confirm the presence of the depression indicated by the remote sensing data. If it were present, on pure physical grounds waters from the southern Ghazal catchment, as from the Rivers Gel, Jur, Tonj and Naam could not leave again, while they were found to be the main sources of discharge. The SRTM data can therefore be judged unsuitable for providing elevation data in this area. Considering the whole Sudd area it will be essential to ground truth any SRTM data before it can be used for e.g. modelling tasks.

2.5 Conclusion

Several major points were investigated in order to set up a realistic model of the hydromorphological conditions in the Sudd.

- The effect of khors on inundation of the seasonal flooded grasslands from the river and their negligible contribution to rainfall runoff into the swamps has been established
- Observations of relative depth and cross section width of main channel, lagoons and swamps, together with flow velocities have led to relative flows through the different elements of swamp cross section. The majority of the flow was found to be carried in the main channel
- Comparison of satellite based DEM data with cross sections and point data from land surveys has identified certain problems. For the southern Sudd area the DEM data can be judged to be suitable for qualitative assessments while for the Bahr el Ghazal area it was found not to represent the conditions on ground. Correcting the DEM with ground control points would be necessary to make it suitable for detailed hydraulic modelling

Chapter III - Spatio-temporal water body and vegetation changes in the Nile swamps of southern Sudan

G. Petersen, J.A. Abeya and N. Fohrer

Advances in Geosciences, Volume 11 (2007), Pages 113-116.

Submitted 15.01.07, Accepted 22.05.07, Published 20.06.07

Abstract

An assessment to describe and quantify the extent of changes in the channel and lagoon system of the Sudd was carried out using Landsat satellite images of 1973, 1979, 1997 and 2002. Using supervised classification and visual interpretation after referencing the images, the water bodies for a representative area between Bor and Shambe (a stretch of 150 km) were delineated. The resulting files were compared to establish and quantify changes in-between the years and as well compared to Lake Victoria outflow data to assess a likely correlation which was found for the largely water level dependent lagoon system. Changes in the channel system were interpreted to happen in a certain pattern but the extent of changes could not be correlated to the outflow data as they are influenced by other, here not considered factors like wind drift and channel blockages by vegetation.

3.1 Introduction

The Nile swamps of southern Sudan, called the Sudd, one of the largest wetland areas in Africa (Mohamed, 2005), represent a highly dynamic system (Butcher, 1938), in which channels, lagoons and inundated areas are constantly interacting and changing in time and space. An aerial overview of typical swamp is given in Figure 3.1. Swamp processes for the Sudd region in general have been described by different authors, e.g. Butcher (1938), Hurst (1932; 1933), Migahid (1948) Mefit-Babtie (1983), Sutcliffe (1957; 1974) and Sutcliffe & Parks (1999), while the extent of changes have so far not been quantified. Water levels and flow velocities interact with vegetation species which in return have an influence on the channel dynamics. Channel blockages by vegetation cause impounding of areas and increased flow elsewhere, wind drift results in movement of floating reed fields.

The main objective of this paper is to describe and quantify the extent of changes in the channel and lagoon system of the Sudd over a period of 30 years. A representative area of the swamps between Bor and Shambe was evaluated in detail regarding the changes which have occurred between 1973 and 2002. The results have been related to the hydrodynamic situation of the period, allowing the assessment of the general trend and behavior of the system in which the meandering channels, moving reed fields and frequent blockages cause challenges for researchers as well as for the economic development of the area.



Figure 3.1: Aerial photograph of the permanent swamp area with channels, lagoons, floating and anchored vegetation areas, taken during an aerial assessment in 2004 over the swamps near Baidit/Padak

3.2 Methods

For the evaluation of the channel and lagoon changes, an analysis of geo-referenced Landsat MSS, TM and ETM band 1/2/3 images (NASA, 2007) of 1973, 1979, 1997 and 2002 for the southern Sudd area between Bor and Shambe as shown in Figure 3.2 has been carried out, comparing and quantifying the changes in open water bodies. A panchromatic combination of band 1, 2 and 3, represented as blue, green and red was used for the current analysis based on a sensitivity analysis where combinations of the different bands were tested for their suitability to provide optimum results. Classification of the channel and lagoon features was then carried out using supervised classification method based on visual interpretation of the images. To assure comparable datasets, images from comparable seasons were selected for the evaluation. Despite the 1973 data which was acquired in February, October images were used for the data evaluation. Possible misinterpretation was eliminated using supervised classification method; matching georeference of the images acquired by the different Landsat sensors was assured by overlaying the images and testing them for their conformity.

3.3 The system

To understand the driving forces of the system, the flow regime as well as the role of the vegetation needs to be understood. Vegetation cover in the Sudd swamps can generally be

classified depending on the elevation of the area above river flood level (Hurst & Phillips, 1938) as

- permanent swamp
- river flooded grasslands (*Toic*)
- rain flooded grasslands
- wooded grasslands (acacia)
- woodlands

Vegetation types are generally distributed in accordance to flooding depth and duration with Lake Victoria outflow being the controlling factor (Migahid, 1948).

The lake discharge is contributing the base flow entering the swamps, superimposed by torrential runoff only during the rainy season and therefore controlling the water levels as it can be deduced from long term data series. The permanent swamp area is mainly inhabited by *Cyperus papyrus*, *Typha domingensis* and *Vossia cuspidata*, while the seasonally river-flooded grasslands are inhabited by *Oryza longistaminata* and *Echinochloa pyramidalis*. *Echornia crassipes* is another species which is increasingly dominating the lagoons. While detailed vegetation maps were not available, it can be assumed that vegetation type and their distribution has changed in concordance with the changes in hydrologic regime over the years.

The vegetation distribution is described in further detail by Sutcliffe (1974); the main species are shown in Table 3.1. The first three species are anchored so their distribution is limited to depth of flooding, for the last three species their root system needs to be in water or saturated soil permanently which gives a good indicator on changing flood patterns. *Phragmites communis*, *Echinochloa pyramidalis* and *Oryza barthii* for example dominate only in areas where the depth of flooding does not exceed 130 cm over a period of ten years or 118 cm for a month in the year. *Cyperus papyrus* needs saturated conditions, can tolerate deep flooding but is limited to a certain range of flooding which appears to be 150 cm (Sutcliffe, 1974). Increasing flood levels will cause these plants to be dislodged from their position and floating downstream which may cause channel blockages.

Table 3.1: Main species inhabiting the Sudd swamps after data from JIT (1954)

Species	Use	Flooding depth	Roots
<i>Phragmites communis</i>		shallow (max 130cm)	buried
<i>Echinochloa pyramidalis</i>	(grazing)	shallow (max 130cm)	buried
<i>Oryza barthii</i>	(grazing)	shallow (max 130cm)	buried
<i>Echinochloa stagnina</i>	(grazing)	deep	superficial/floating
<i>Vossia cuspidate</i>		deep	superficial/floating
<i>Cyperus papyrus</i>		deep	superficial/floating

Also reports of Euroconsult (1981) describe the phenomenon of channel blockages which can further on be proven by aerial observation and Landsat satellite image evaluation where the lighter green shade of newly grown reeds in blocked river channels is distinguishable from the darker green of older vegetation.

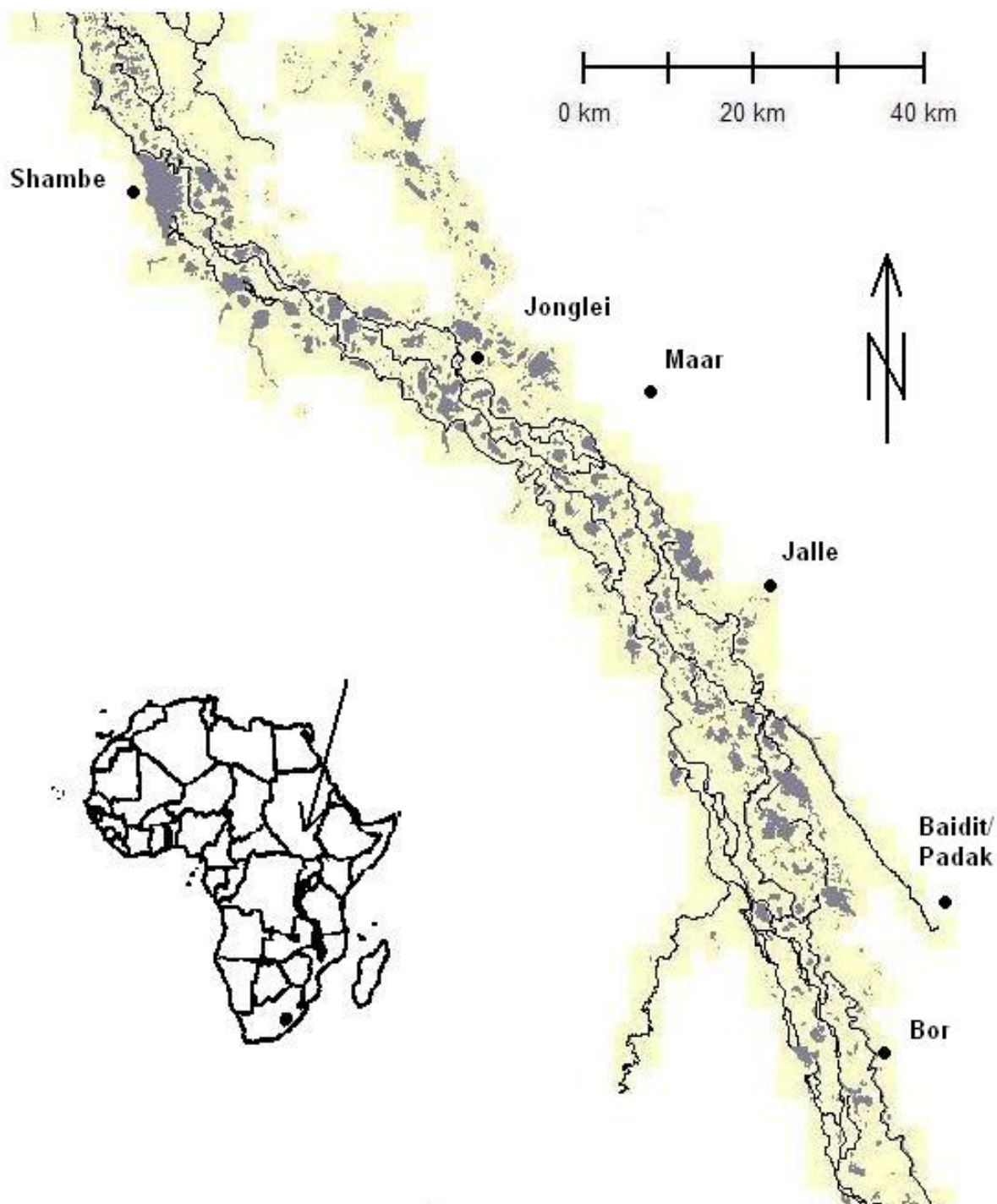


Figure 3.2: Area overview map derived from Landsat image interpretation

3.4 Results

The evaluation of the datasets shows that the main channel system is stable; channels generally decrease in width and move in an upstream direction as shown in Figure 3.3. The significant

trends can mainly be observed at bends and along straight channel sections, where the channel movements exhibit a typical pattern by moving outward between 1973 and 1979 and then again slightly inward between 1979 and 1997/2002. Movements can be quantified with up to 200 m over the 30 year period of investigation. No significant trends can be observed between the 1997 and 2002 datasets where changes are erratic and do not follow a defined pattern.

Lagoons show a different trend, with the location of the main lagoons being stable in location but showing a tendency of decreasing in size as visible in Figure 3.4, a phenomenon which correlates with the decreasing Lake Victoria outflows during the period of investigation leading to lower water levels followed by an increase of vegetation growth in the now habitable areas with less water depth. For the area of investigation between Bor and Shambe the area of open water bodies decreased by 38% in surface area between 1973 and 2002. The Shambe lagoon as an example decreased in size from 30.4 km² to 27.0 km² in surface area. A decrease in channel width, considering the main channels over the same period is quantified with 34%, e.g. for the main channels at Jonglei latitude from 97 m to 74 m in width in average. Movement of channel boundaries is thereby significant so that errors which may have been introduced during data acquisition and processing can be neglected.

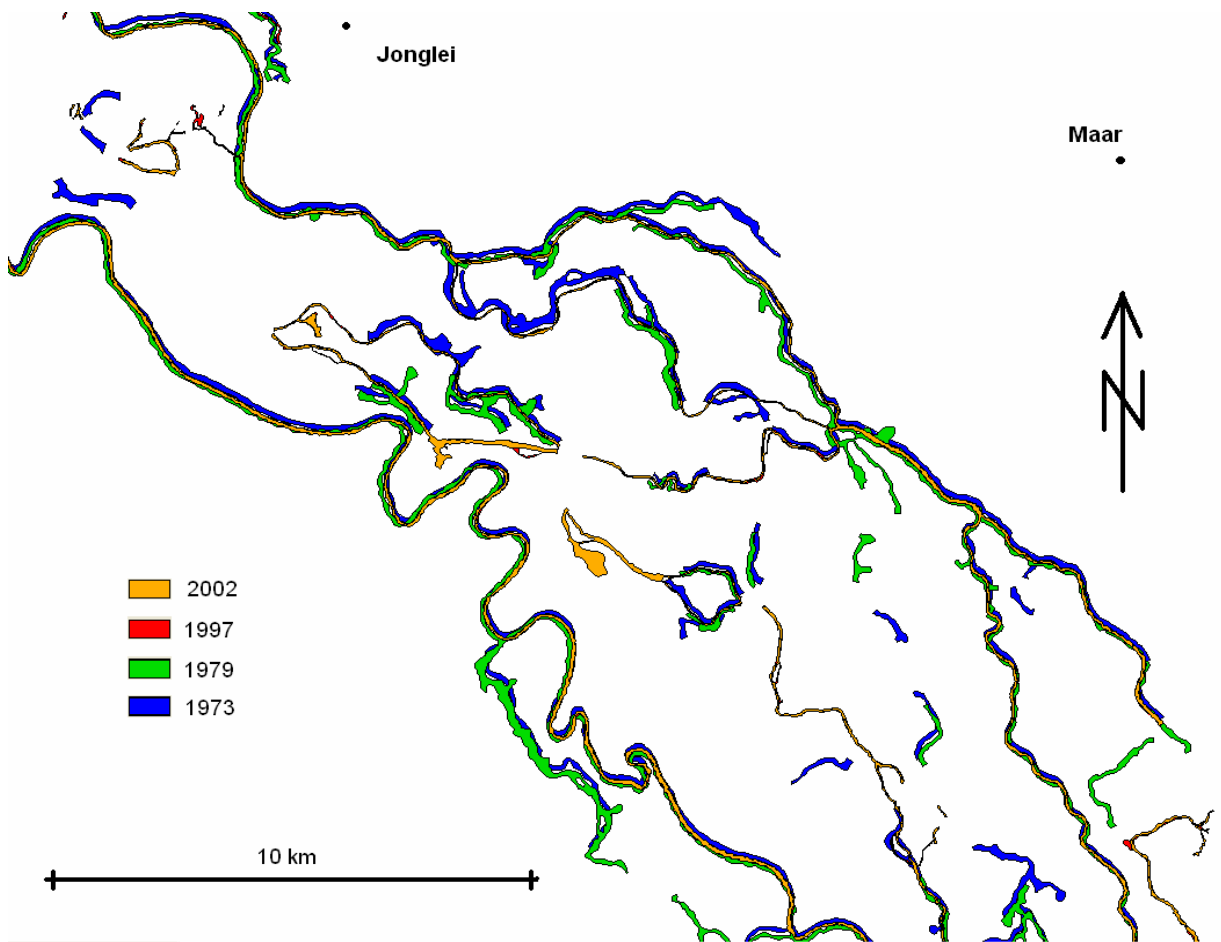


Figure 3.3: Overlaid channel system of the years 1973, 1979, 1997 and 2002 of the area of Maar – Jonglei, indicatively showing the general trends of channel movements and decrease in channel width

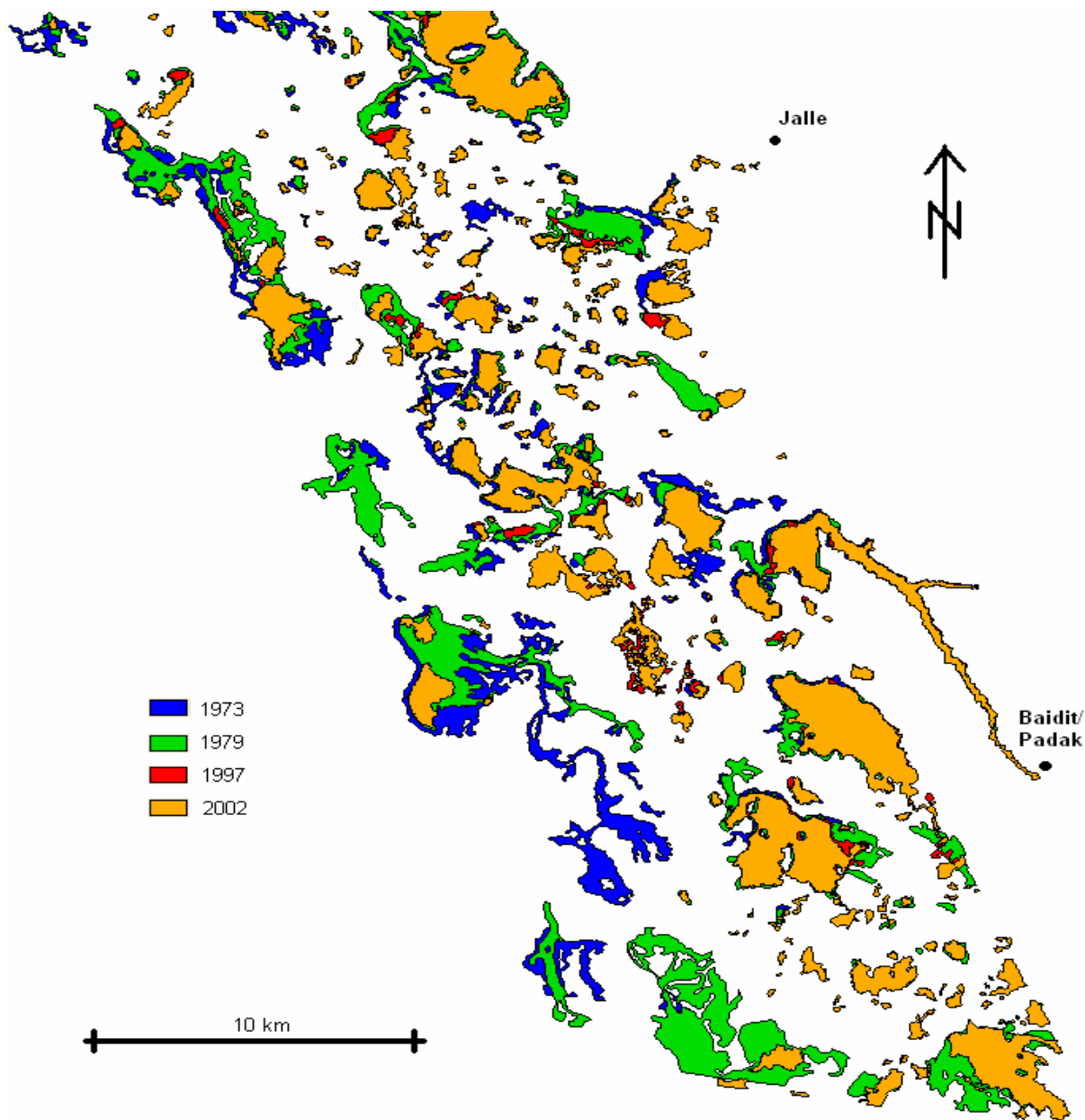


Figure 3.4: Overlaid lagoon system of the years 1973, 1979, 1997 and 2002 of the Padak - Jalle area indicating the decrease in lagoon area

Evaluation of channel changes in relation to extreme flow events considering the different conditions between the investigated points in time leads to no clear trend. 1973 data shows the situation after average flow conditions as shown in Figure 3.5. The following 1979 data pictures the situation after the 1978 high flow conditions with the respective high flood levels, the situation until 1997 then shows average to below average flow conditions, while in 1998 another peak event was recorded. Evaluating the spatial datasets in respect to these flow conditions as shown in Figure 3.5 does not yield a significant relation to these. A clear linear relation of changes of the swamp system to the described flow conditions can therefore not be deduced as flow events are not matching with the observed changes in the channel system. It

needs to be assumed that other factors like e.g. wind drift and channel blockages as well as long term effects play a significant superimposing role as well.

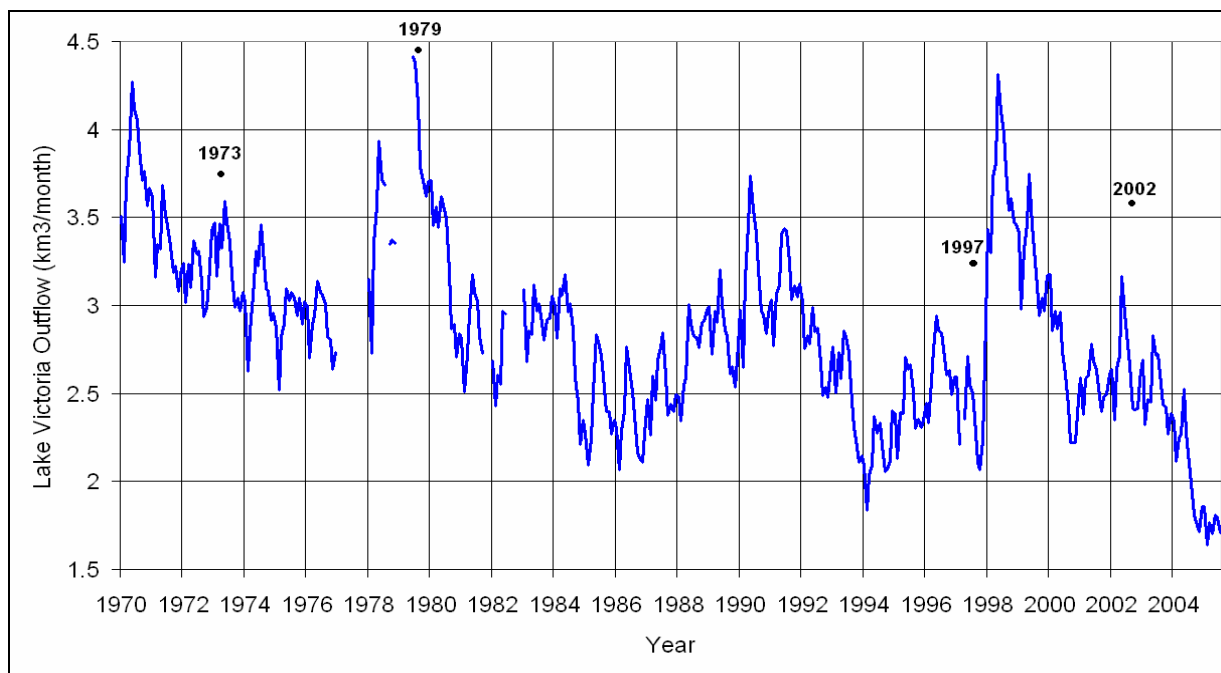


Figure 3.5: Lake Victoria outflow at Jinja (after data from Hurst, 1933 and supplements) with marked years of evaluated satellite data

3.5 Discussion

An assessment was carried out to describe and quantify the extent of changes in the channel and lagoon system of the Sudd between 1973 and 2002. Results show clear trends of channel movements with time while no linear correlation can be established to Lake Victoria outflows. Lagoon sizes and channel width on the other hand show a decreasing trend, which in general matches with the decreasing lake outflow, a finding that corresponds with the fact that swamp vegetation is water level dependent and that more swamp area becomes habitable for *cyperus papyrus* with decreasing water levels.

The factor that a correlation could be established for the lagoon and channel sizes but not for the channel movements is assumed to be related to the more complex range of factors influencing channel movements which have not been captured in the assessment. As described by Koponen and Kumm (2004), channel blockages can have large impacts on local water levels and other factors like wind drift have been observed to have a significant influence on the floating reed fields. Varying combinations of these short term factors – general discharge related water levels, current velocities, wind drift and blockage related water level changes – therefore randomly alter the system not allowing for a general prediction of magnitudes of changes. As a trend, but not in linear correlation to the discharges, a general downstream movement of the channels is visible from image interpretation, the movements at the bends being of greater magnitude than along the straight channel sections, a fact assumably caused by

increased erosion forces along the outsides of the bends as it can generally be observed in meandering river systems.

3.6 Conclusions and future perspective

Spatio-temporal water body changes in the Sudd swamps of southern Sudan can be captured and evaluated and quantified using Landsat satellite data. Correlation between lagoon size and lake discharge is established, while channel changes can not be directly related to Lake Victoria outflow. For a detailed assessment of the channel changes, next to the factors as described above, also ground referenced vegetation maps in fine spatial resolution would be needed as the type of vegetation is, also concerning the ground level it indicates in the swamps, of significant importance for a detailed assessment of channel changes.

Chapter IV - Water balances of the Vertisol floodplains of southern Sudan

G. Petersen and N. Fohrer
Hydrological Sciences Journal
Submitted 19.11.07

Abstract

The water balances of the floodplains of the Sudd swamps in southern Sudan are, while dependent on the river levels, influenced by a complex interaction between the soil, the vegetation, the topography and seasonal trends in rainfall and evapotranspiration. Based on field measurements, these components have been assessed in detail and evaluated regarding their function in the seasonal cycle of flooding and drying. A detailed analysis of the soil and evapotranspiration conditions as well as the interaction with vegetation and meteorological conditions using field and laboratory experiments has been conducted. Sources, processes, flow directions and the fate of the floodwaters on both the river fed seasonal floodplains and the rainfed grasslands have been established showing that river spill is responsible for area flooding while no return flow occurs and drying is caused by evapotranspiration. Rainfall can only cause temporary flooding in extreme events.

Keywords: Evapotranspiration; Soil water recharge; Nile; Sudd swamps; Flood; Water budget

4.1 Introduction

The Sudd swamps of southern Sudan, one of the largest wetland areas in Africa, are defined by seasonal flooding and are responsible for the loss of large quantities of the inflowing waters of the White Nile, here called the Bahr el Jebel. Evaluating flow data from Hurst (1933 and supplements), approximately half of the inflowing waters are lost between Mongalla and Malakal, the respective entrance and exit of the swamp system.

Historical information about the region is mainly available from studies carried out during the last century. Hurst & Phillips (1931, 1938) and Butcher (1938) were the first to carry out intensive research in the Sudd swamps describing hydrometeorological conditions. Shrinking and swelling of the Sudd soils was investigated by Migahid (1948). The Jonglei Investigation Team (JIT) (1954) mapped the soil types of the Sudd and defined the area in the immediate vicinity of the swamps as sudd or *toic* soils. Mefit-Babtie (1983) collected humidity, sunshine and temperature data during the Jonglei Canal studies at Bor and Malakal, and described the seasonal cycle of water logging and desiccation leading to deep cracking of the soil. Wright, in JIT (1954) gave initial hints on soil water recharge assuming values between 300 and 800 mm,

assuming that latter was overestimated. Sutcliffe (1974) described the vegetation distribution of different species in the swamps and Petersen (2007a) described the vegetation dynamics with regard to changes in the permanent swamps. Hurst & Phillips (1938) and Migahid (1948, 1952) reported outcomes of different evapotranspiration experiments. Sutcliffe & Parks (1999) considered evapotranspiration with a value of 2150 mm per year. The influence of the area morphology on flooding was described by Petersen (2007b) evaluating flooding conditions in local depressions.

While historically a great amount of information was collected, a comprehensive analysis of the water balances of the floodplains is not available and the different historical studies focused on their different specific fields of investigation. While these studies give a good overview of the system, the water balances of the seasonal flooded grasslands, the *toic*, have so far not been described under consideration of all involved factors.

The floodplains are an important feature of the area concerning their ecological and economical value. Detailed knowledge of their function, especially their water balances which are the driving factors for vegetation growth is important for a full understanding of the system and future planning tasks. The objective of this paper is this investigation of the processes and mechanisms of the flooding and drying cycle of the *toic*, describing the water budget over the year. Specific objectives comprise the assessment of individual parameters of soil and vegetation in combination with precipitation and evapotranspiration as well as an evaluation of interdependencies.

4.2 Materials and methods

4.2.1 The study site

The study of the flooding and drying mechanisms of the Vertisol floodplains of southern Sudan was carried out in the Bor - Jonglei area, a 100 km stretch of land in the southern part of the Sudd swamps along the right bank of the Bahr el Jebel as shown in Figure 4 1.

The area has a flat topography as described by Petersen (2007b) and is dominated by the annual cycle of flooding and drying caused by river flooding and heavy rainfall. The soils of the Sudd region are typical African floodplain black cotton soils with high clay content, classified as Vertisols (IUSS Working Group WRB, 2006).

The plains flood in an annual cycle related to the rainy season with respective local rainfall and increased river discharges leading to overbank spill (Sutcliffe & Parks, 1999). In the dry season the soils are drying which leads to heavy cracking. During this period the grassy vegetation dies and the residues are typically removed by bushfires. With the onset of the rains, vegetation growth is starting again.

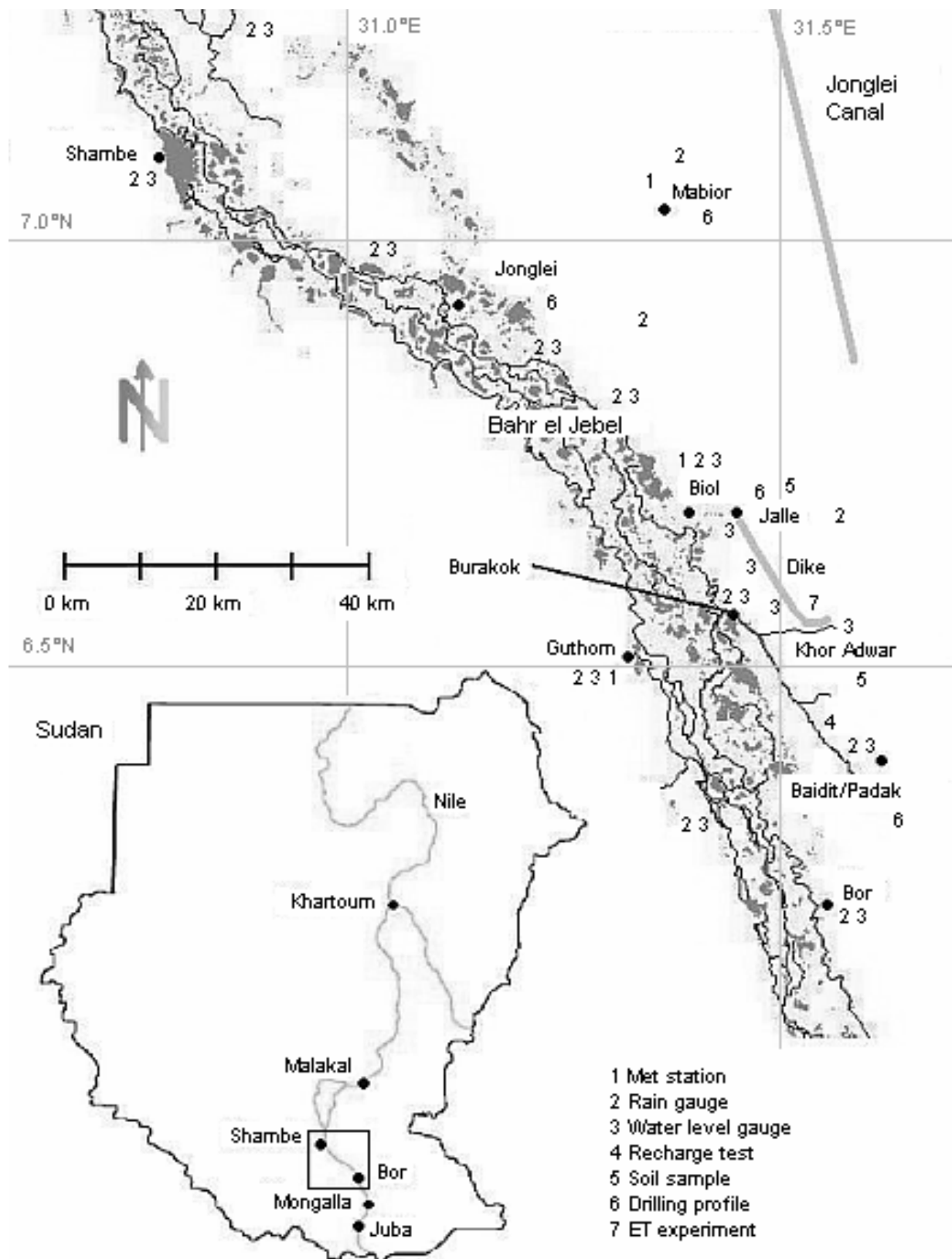


Figure 4.1: Overview of the Sudd swamps between Bor and Shambe. The image shows main channels and lagoon areas.

4.2.2 Geology

Five drilling profiles, available through borehole drilling records from OLS Water, Kenya, were used to investigate the geological situation of the area between Bor and Shambe; the locations are shown in Figure 4.1. In addition to the evaluation of the drilling profiles, the soil profile was assessed in nine up to 8 m deep borrow pits between Baidit/Padak and Jalle.

4.2.3 Soil Analysis

Soil samples were taken in 2005 at distances of 25 and 50 km north of Bor on the eastern bank of the Bahr el Jebel from within the seasonally flooded grassland area near to the villages of Baidit/Padak and Jalle respectively (Figure 4.1). A total of six samples were taken from different depths between 1 and 4 m within excavation pits. As previous tests in eight borrow pits (Petersen, 2006) had shown the soil profile to be very comparable and homogenous, results have been averaged for the surface (< 1 m) as well as for the deeper subsurface (> 1 m) layers.

Grain size distribution was analyzed based on DIN 11277 (1994) using a combination of sieving and sedimentation method after extraction of soluble salts, carbonates and organic matter. As part of the preparation of the soil samples for the grain size analysis, the organic content and carbonate content were extracted using H₂O₂ and HCl respectively.

Classification of the soil type was conducted using the USDA Field Book for describing and sampling soils (Schoeneberger, 2002) using the combined texture triangles based on grain size distribution analysis and the IUSS Working Group WRB (2006).

The hydraulic conductivity was assessed using k_f -cells in accordance with German DIN 18130 (1998). Resulting k_f values were reported in m/s.

Shrinking and swelling of the soil were analyzed using volumetric difference calculations comparing the volume of the soil found under saturated conditions with its volume when dried. The analysis was carried out using a water replacement test where the volume of water displaced by saturated and dried soil samples was compared.

4.2.4 Soil water recharge

Soil water recharge was assessed through field experiments conducted at different locations on the seasonally flooded grasslands in the Baidit/Padak area approximately 25 km north of Bor between May 2005 and August 2006. A simple field infiltrometer was used for this task. The device consisted of a square metal frame 50x50 cm in width and 30 cm in height. This frame was sunk into the ground to a depth of 5 cm. The location for the experiment had to be carefully selected to avoid the several meter long cracks which would have drained away the water quickly. The frame was then filled with water and the decrease in water level recorded in 10 minute intervals until stagnant conditions were observed. To avoid seepage from within the frame into the adjacent soil, the area surrounding the frame was watered at the start of each experiment and kept saturated throughout the recording time.

In addition to the above *in situ* experiments, laboratory tests were conducted where the difference in soil water content between saturated and dried (and cracked) core samples was determined. The sample cores were saturated, weighed, then dried, weighed again and the difference calculated.

4.2.5 Soil Evaporation

Soil evaporation as present under conditions when no or only dead vegetation is available was assessed using undisturbed surface soil samples, partly with limited dead vegetation to resemble natural conditions. The tests were conducted in Baidit/Padak, where samples were placed in a 300 mm diameter pan and saturated with water. The sample was shaped to be level with the pan, limiting the evaporation to the soil surface area. The weight of the pan was recorded at hourly intervals and the moisture loss per time step deduced from the records according to Formula 1. Experiments were carried out day and night between January and May 2006 with different cloud conditions to achieve average results.

$$EV = (m_x - m_{x+1}) / (a_{\text{surface}}/1000) \quad (1)$$

With EV = Evaporation (mm)
 m_x = weight at timestep x (g)
 m_{x+1} = weight at timestep x+1 (g)
 a_{surface} = surface area (mm²)

4.2.6 Rainfall measurements

Rainfall data were collected beginning in April 2004 at one location in Baidit/Padak using a standard rain gauge. The station network was then expanded in 2005 and from March 2005 to August 2006 field data were recorded at 15 stations in the swamps and on the seasonally flooded grasslands between Bor and Shambe in daily and hourly intervals. The locations are shown in Figure 4.1. Texas Electronics TE525-L tipping bucket rain gauges in combination with Campbell CR10X data loggers were used for this task.

4.2.7 Recording of meteorological data

Additional meteorological data have been recorded using the Campbell monitoring stations in a period between April 2005 and August 2006 in daily intervals. Recorded parameters comprised wind speed measured with 014A-L Met One anemometers at Guthom and Mabior at a height of 2.0 m above ground and solar radiation measured with CM3 Kipp & Zonen pyranometers as well as humidity and temperature measured with CS500-L and 108-L probes at Biol and Guthom, for which the sensors were added to the CR10X data loggers.

4.2.8 Water level records

Recording of water levels commenced in January 2005 with basic staff gauges in the seasonally flooded grassland area. The system was improved in April 2005 through the setup of automatic Campbell gauges equipped with CS420-L pressure transducers and CR10X data

loggers at different locations in the swamp area between Bor and Shambe. The gauges were positioned at locations along the main channels as well as in the lagoons. The records were recalculated to a local survey datum yielding comparable data series. In addition to the automatic records, measurements were taken at Khor Adwar and along a newly constructed dike line on the seasonal flooded grasslands between Khor Adwar and Jalle in 4 km intervals. All data was logged in daily intervals, gauge locations are shown in Figure 4.1.

4.2.9 Vegetation observations

Vegetation and environment within the seasonally flooded grasslands between Baidit/Padak and Jalle were observed on a monthly basis between April 2004 and August 2006. Based on photographs, the state and changes of vegetation, soil condition and flooding were assessed to be compared with the meteorological measurements.

4.2.10 Actual evapotranspiration

An evapotranspiration experiment was conducted in October and November 2005 as well as in January 2006 using a naturally vegetated depression which was flooded in the rainy season and drying out slowly after the end of the rains. The 900 m² depression received its input through precipitation within its perimeter and was isolated from other sources of flooding. The natural vegetation of the depression was representative for the grassland area, and it was protected from animal access.

Precipitation within the depression was recorded using a standard rain gauge situated within the perimeter. Water level changes, from which evapotranspiration was deduced, were recorded by a measuring rod. Daily actual evapotranspiration values were calculated using Formula 2. Percolation was neglected due to the prevalent soil conditions. Cloud conditions were recorded together with the data. Problems arose in accessing the site after heavy rain events so that measuring intervals varied slightly.

$$ET_a = wl_x - wl_{x+1} + p \quad (2)$$

With ET_a = actual evapotranspiration (mm)
 wl_x = waterlevel at day x (mm)
 wl_{x+1} = waterlevel at day x+1 (mm)
 p = precipitation (mm)

4.2.11 Evapotranspiration calculations

Evapotranspiration was calculated based on meteorological records of monitoring stations located within the swamp and seasonally flooded grassland area as shown in Figure 4.1. The FAO Penman-Monteith method (Allen *et al.*, 1998) was used in a spreadsheet calculation to determine ET_C , the evapotranspiration under given conditions.

Values used in the calculation were selected from the October/November 2005 measuring period for which also the evapotranspiration experiment had been carried out. The values used

for an average calculation for this period are shown in Table 4.1. In addition a daily time series was calculated using the respective daily input values measured in the same period. Based on the validated results monthly average evapotranspiration was calculated for a whole year using the vegetation observations to deduce adjusting coefficients for the given conditions.

Table 4.1: Parameters and values used for average evapotranspiration calculations after FAO Penman-Monteith for the October/November 2005 period

Parameter	Value	Unit
Elevation	423	m
Mean daily temperature	24	°C
Max daily temperature	34	°C
Min daily temperature	21	°C
Wind speed	2	m/s
Relative humidity	80	%
Sunshine hours	9	h
Daylight hours	12	h
Latitude	6.5	°N
Condition coefficient K_C	0.8	-

4.3 Results

Next to the area morphology with its very gentle gradients (Petersen, 2007b) and respective limited overland flows, soil characteristics and vegetation are, in combination with rainfall and evapotranspiration, the most important factors controlling the flooding and drying processes of the seasonal flooded grasslands of the Sudd area. For a better understanding of the progress and retreat of the flood waters, the individual factors of influence are described in detail followed by a detailed assessment of the water balances.

4.3.1 Surface geology

Drilling records for the Bor – Shambe area show a situation where sandy sub-layers are overlaid by a 12 to 20 m thick highly impervious clay layer. Soil samples taken from borrow pits confirm the presence of the upper clay layer. The drilling locations are shown in Figure 4.1; the obtained profiles are shown in Figure 4.2.

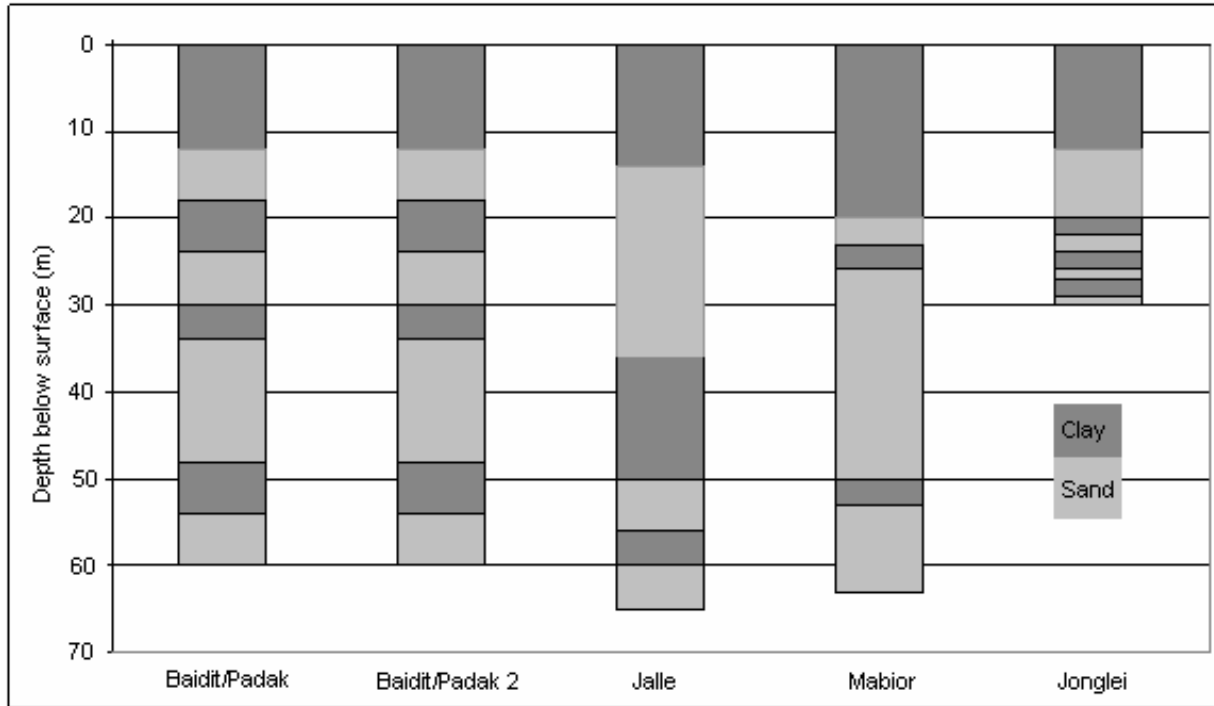


Figure 4.2: Geological cross section generated from drilling profiles of the Bor – Shambe area from OLS Water, Kenya

4.3.2 Soil Analysis

The soils of the project area are typical Vertisols as described by the IUSS Working Group WRB (2006). The soils, described after Munsell, show an olive black colour (5Y 3/2) for the surface layer and change from grey to olive with the deeper layers showing variations of 5Y 4/1 to 5Y 4/4 respectively. Calcretions increase in size and number with the deeper layers.

The soil samples consist of “sandy clay loam” for the surface layer < 1 m depth and “sandy clay” for the deeper layers > 1 m depth after the USDA Field Handbook for describing and sampling soils (Schoeneberger, 2002). The relatively lower clay content is found in the surface layer.

Grain size analysis show clay contents between 25 and 49 percent. The results for the averaged surface and subsurface layer samples are shown in Figure 4.3.

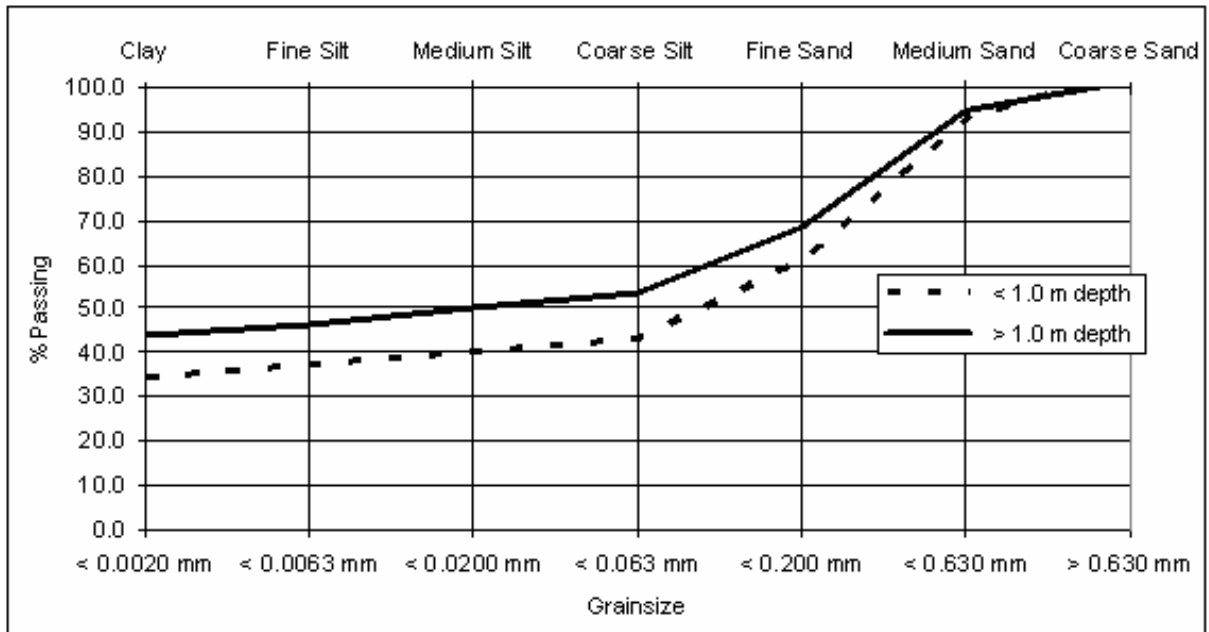


Figure 4.3: Grain size distribution of averaged surface (< 1 m depth) and subsurface (> 1 m depth) soil layers

The hydraulic conductivity of the soil samples indicates highly impermeable conditions with k_f values of $1.1E-11$ and $2.1E-10$ m/s for the surface and subsurface layers respectively. The higher impermeability is found in the surface layer.

A shrinking test conducted with the different samples yielded results between 11.4 and 31.5% shrinkage from saturated to dry condition. Averaged values show shrinkage of 15.4 and 29.5% for the surface and subsurface layers respectively.

4.3.3 Soil water recharge

Results of the soil water recharge experiments show that values vary with rainfall over the season and exceed 350 mm when the soil is dry. Figure 4.4 shows the influence of precipitation in the rainy season on the recharge. The fact that even within the rainy season a certain amount of recharge occurs can be explained by the magnitude of evapotranspiration. This exceeds precipitation leading to unsaturated conditions in non flooded areas which affects soil water recharge rates. It needs to be noted that the experiments were conducted at locations where water was not ponding.

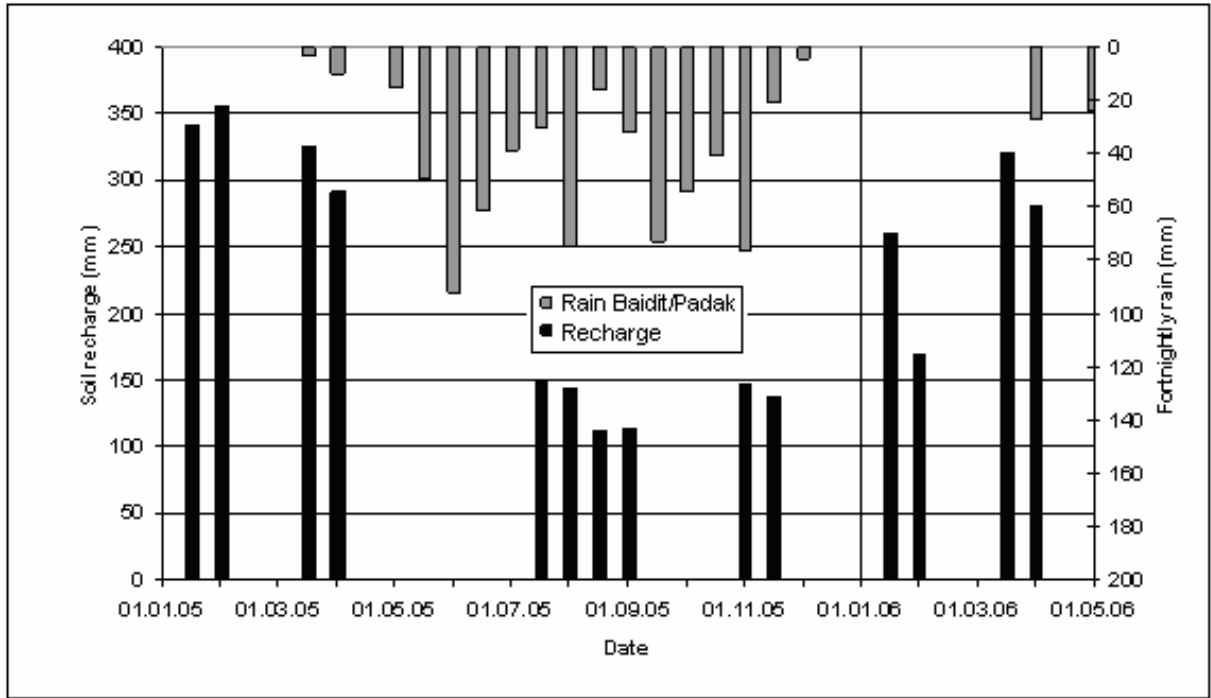


Figure 4.4: Soil water recharge and rainfall between January 2005 and April 2006

Initial infiltration rates were recorded in order to quantify the amount of water that can be taken up by the soil during heavy rainfall events. Values between 22 and 128 mm/10min for the initial 10 minutes of the experiment were recorded, the average value being 77 mm/10min.

Laboratory tests show a high soil water recharge capacity with moisture contents ranging between 30 and 51%. For the surface and deeper layers the respective average values are 35 and 45%. These values can not be directly related to recharge values in mm but confirm the high recharge capacity of the soils.

Soil cracks which provide access for water to reach deeper layers before these cracks close are a factor to be taken into account. The influence of the cracks could not be assessed with the used methods, the recharge values therefore can be assumed to be underestimated.

4.3.4 Soil evaporation

Evaporation from moist soil with no or only dried vegetation as it occurs in the dry season was measured to assess the amount of water evaporated by bare soil at the start of the rainy season before flooding and vegetation growth in line with transpiration occurs.

Results show evaporation values which vary depending on the time of the day reaching up to 1.5 mm/h at noon. Daily evaporation averaged as 10.5 mm. The average hourly results are shown in Figure 4.5.

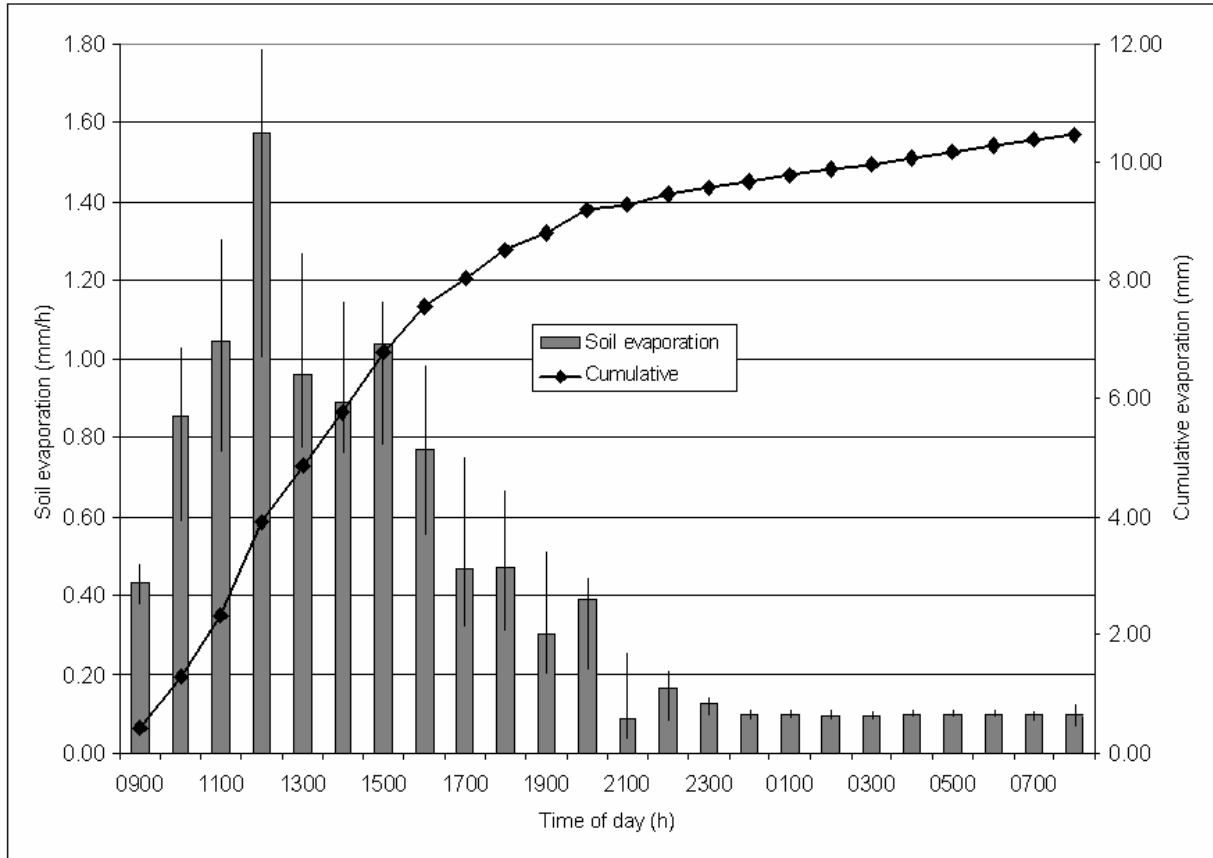


Figure 4.5: Soil evaporation values during an average daily cycle

4.3.5 Rainfall data

An average of 757 mm of annual rainfall has been measured for the different stations in the Bor-Shambe area between April 2004 and August 2006. The results indicate relatively dry conditions in comparison with long term measurements which show average rainfall of 847 mm per year in this region evaluating Hurst & Black (1943 and supplements) data for 1905 to 1981. Results show the rainy season lasting from late March to early November. Rain events are mostly of short duration of maximum one hour. During this time up to 73 mm/h were recorded while an average rain event provided 14 mm/h. The spatial distribution of rain events is highly randomly. While the general trend and cumulative amount of rainfall at all monitoring locations was comparable, the daily intensity varied widely between no rain and considerable downpours.

4.3.6 Other Meteorological data

Wind speed measurements range between 0.9 and 5.9 m/s daily average wind speed, showing an annual average value of 2.1 m/s. The highest values occur in April before the start of the rains. For the October/November period in which the depression experiment has been conducted the wind speed averages at 2.0 m/s. Over the year temperatures range between 18 and 39°C, humidity ranges between 46 and 89% and daily global solar radiation averages at 24 MJ/m².

Results are shown in Table 4.2. Daily sunshine and daylight duration have been measured with an average of 9 and 12 hours respectively.

Table 4.2: Meteorological data for the Bor – Shambe area. Monthly averages for April 2005 to August 2006

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Windspeed (m/s)	2.2	1.6	2.1	3.1	2.4	2.0	1.7	1.7	1.8	2.0	2.0	1.9
Temperature (°C)	27.2	28.5	29.5	28.9	26.6	26.3	26.1	25.8	24.5	24.1	24.5	26.5
Daily solar radiation (MJ/m ²)	21.3	22.4	25.8	24.6	26.9	23.5	23.5	25.1	25.0	22.0	22.7	21.1
Relative humidity (%)	52	46	56	70	78	84	89	88	85	80	78	58

4.3.7 Actual evapotranspiration

Evapotranspiration values deduced from the depression experiment have been established with an average of 7.3 mm/d for both the October/November 2005 and January 2006 periods, the daily values are shown in Figure 4.6. Fluctuations in the daily evapotranspiration rates correlate with weather observations showing reduced evapotranspiration on cloudy days and higher values on sunny and windy days. Percolation has been neglected considering the impermeable soil conditions.

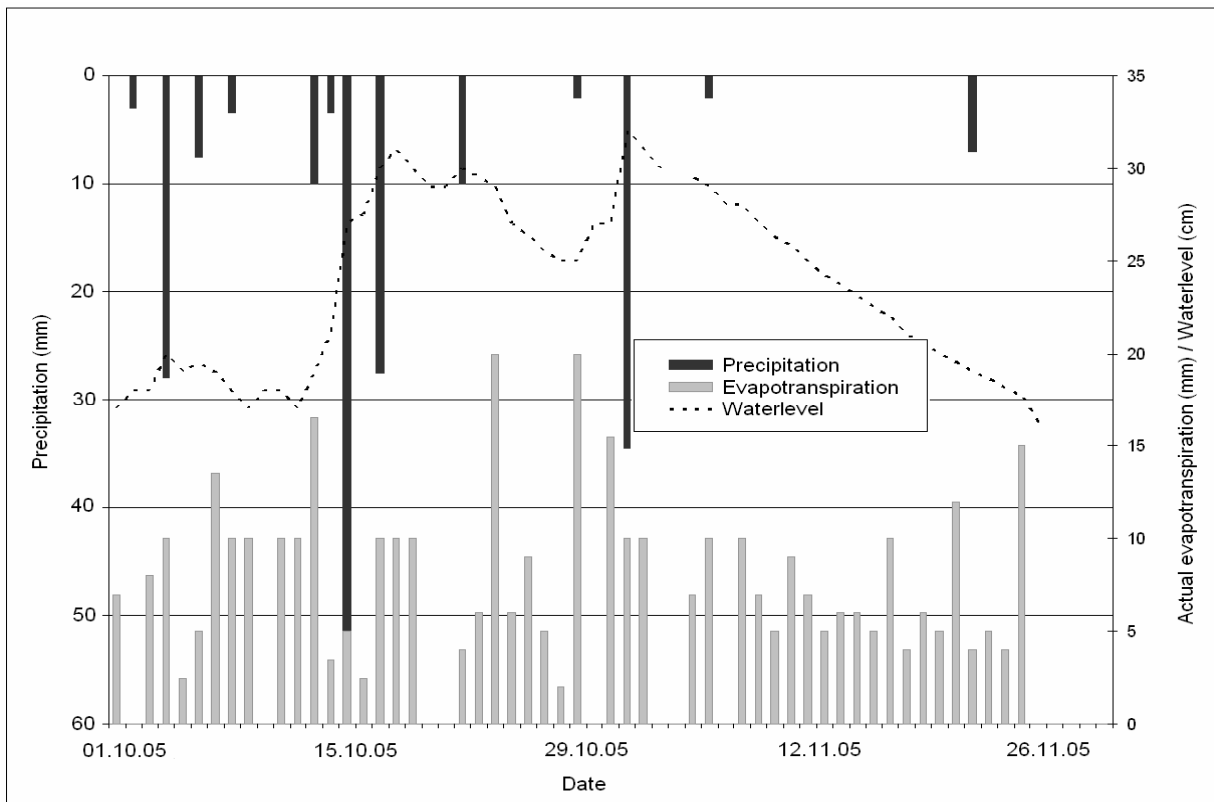


Figure 4.6: Evapotranspiration from the October/November 2005 depression experiment showing daily evaporation rates as well as correlation between rainfall events and water level fluctuations

4.3.8 Evapotranspiration calculations

Average evapotranspiration for the October/November 2005 period was calculated at 7.3 mm/d based on daily temporal resolution using the FAO Penman-Monteith equation. This value was calculated using the standard settings together with a condition coefficient of 0.8 based on the vegetation conditions in the depression. The result provides a good match to the measured 7.3 mm/d obtained in the depression experiment. The comparison is shown in Figure 4.7. Fluctuations of the measured values are obvious while the general trend correlates. The fluctuations can be explained by the daily measuring time step which is coarser than typical rainfall events of one hour. The readings therefore strongly depended on the time lag between rain event and measurement as well as slightly varying measuring intervals due to accessibility reasons after rain events.

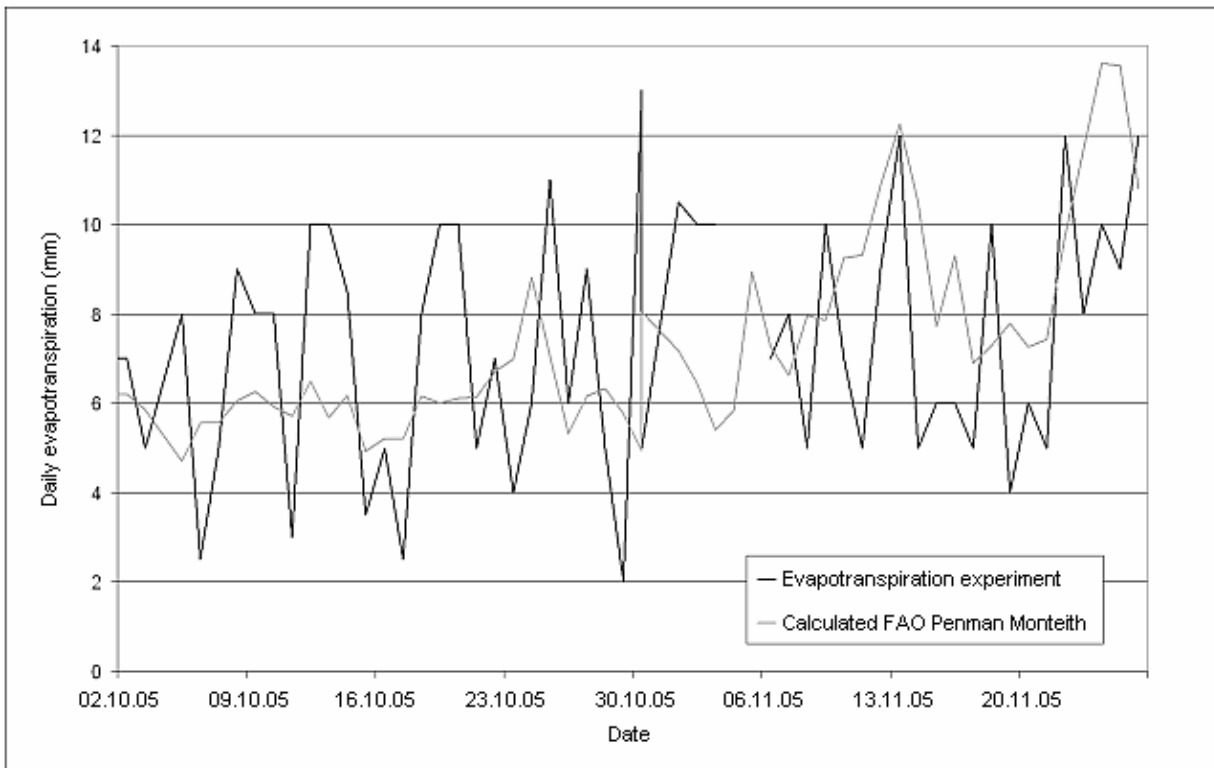


Figure 4.7: Comparison of calculated and measured daily evapotranspiration values

Year round evapotranspiration values calculated with the FAO Penman-Monteith equation in monthly resolution are tabulated in Table 4.3. The total evapotranspiration per year is calculated as 2075 mm. The value of 1.9 mm/d for January differs from the depression experiment due to different water availabilities between the depression and the surrounding, at this time drier, area.

Table 4.3: Evapotranspiration values calculated after FAO Penman-Monteith for the Bor – Shambe region

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average ET (mm/d)	1.9	0.2	0.2	7.0	9.6	10.0	7.7	6.6	7.6	7.8	6.3	3.1

4.3.9 Vegetation condition

Vegetation conditions were established from observations in the seasonally flooded areas. The pattern follows the hydrological cycle and the vegetation reacts to the availability of water. The grasslands are mainly inhabited by grassy species of which *Echinochloa pyramidalis* (Antelope Grass), *Echinochloa stagnina* (Hippo Grass), *Vossia cuspidata* (Hippo Grass), *Oryza barthii* (Wild Rice) and *Oryza longistaminata* (Wild Rice) are the most common ones that have been observed. During the annual cycle of flooding and drying the vegetation follows the pattern of water availability. Growth starts after the first rains in April and reaches its peak in July at the peak of the floods where large areas are inundated and the grass overgrows the whole water body. With decreasing flood levels also the vegetation deteriorates and dries quickly after the end of the rainfall period. In November the grass starts to burn in patches and by January all grass is burnt with the bare soil exposed until the next growing cycle starts again. The pattern is shown in Figure 4.8.

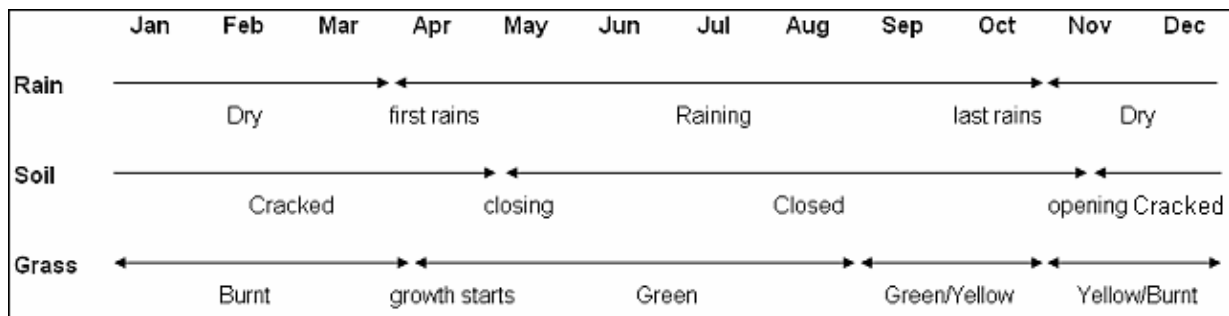


Figure 4.8: Observed conditions in the seasonal flooded grassland areas

4.3.10 Observation of short distance water level fluctuations

Observations of water level fluctuations in the seasonal flooded grasslands were compared with water level changes in the permanent swamp and with rain events. Results as displayed in Figure 4.9 show that water levels on the floodplains precisely correlate with the water levels in the permanent swamp area. No direct correlation could be established between rainfall events and water level fluctuations on the floodplains which indicates the small influence of rainfall on the water levels. During the receding of the floods in November 2005, flood water levels on the floodplains have been observed to decrease with on average 5 mm/d simultaneously at all stations. Compared to this, the nearby Burakok level within the permanent swamps still showed higher water levels.

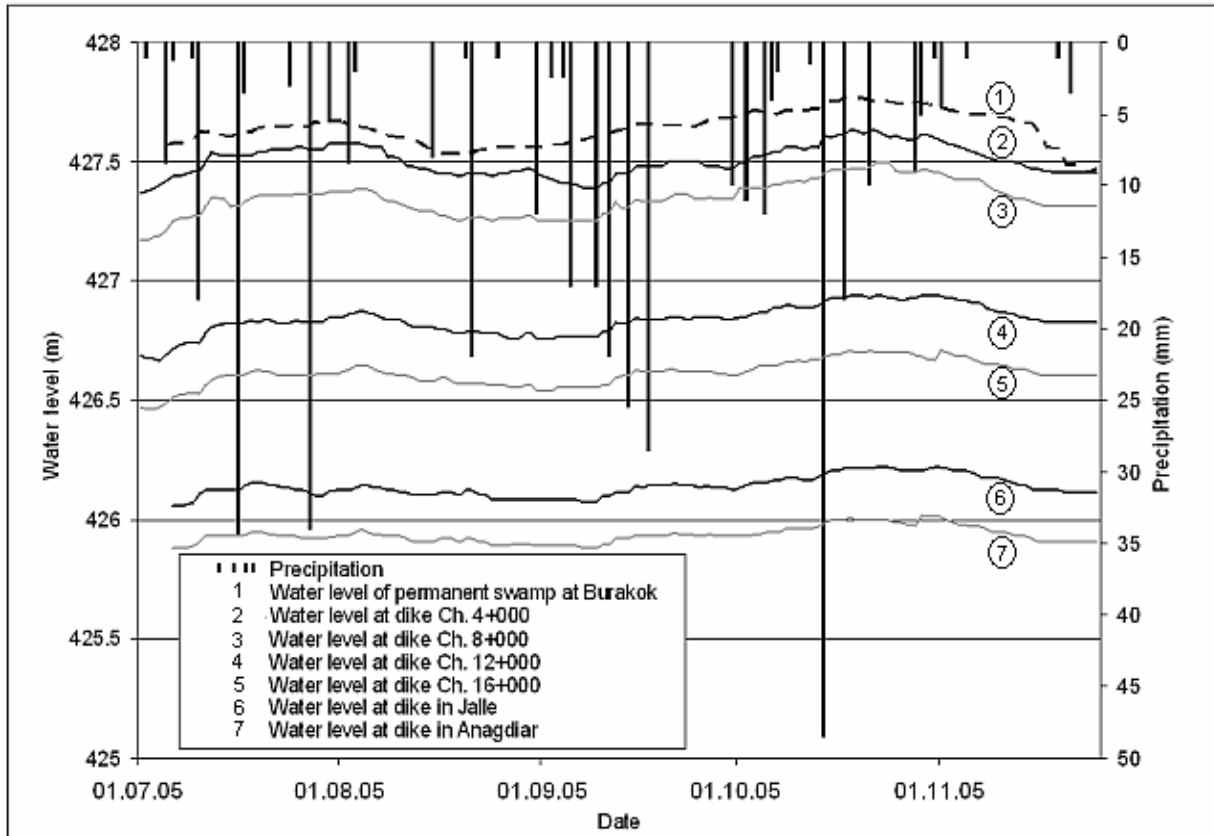


Figure 4.9: Water level fluctuations at different locations in the seasonal flooded grassland area compared to levels at Burakok station within the permanent swamps

4.4 Discussion of flooding and drying mechanisms

4.4.1 Components of flooding mechanism

While the influence of the area morphology with regard to its influence on large scale flooding was discussed by Petersen (2007b), local flooding mechanisms of the floodplains are, next to the water levels in the permanent swamp, influenced by different parameters. These include the soil, the vegetation and the meteorological conditions influencing evapotranspiration. Sources of flooding can generally be divided into waters spilled from the swamps and rainfall. The former causing widespread and long term flooding of the seasonally flooded grasslands, the latter may cause short term shallow flooding in the rainfed grasslands if soil water recharge capabilities are exceeded. The general discrepancy between the measured 757 mm of annual rainfall and 2075 mm of annual evapotranspiration highlight the water deficit in the area.

Results show that the soil recharges up to 350 mm of water when dry, which can be assumed to be underestimated as the influence of soil cracks has not been taken into account during the recharge experiments. Only after this amount of water has been recharged, flooding will start. The result is higher than the value of 200 mm proposed by Sutcliffe & Parks (1999) while in the lower range of the 300 to 800 mm range which Wright in JIT (1954) suggested. Later in the

rainy season the partially saturated soil will recharge until, depending on the conditions, full saturation is reached. Depending on the state of the vegetation which may vary between burnt soils and fully developed grass cover, soil evaporation can reach 10.5 mm/d and evapotranspiration can reach 10.0 mm/d as a monthly mean in the month of June. The average annual evapotranspiration rate of 5.7 mm/day (2075 mm/year) is similar to the value stated by Sutcliffe & Parks (1999) who estimated a value of 2150 mm. Deep percolation can be neglected considering the impermeable clay top layer in the soil profile (Figure 4.2).

Timeframes play an important role in combination with these mechanisms. Single rain events typically provide 14 mm precipitation on average and 73 mm as a maximum measured event within a short timeframe of less than one hour and in locally restricted areas. Soil water recharges with an average initial recharge capacity of 77 mm/10min depending on initial soil saturation conditions. Depending on the season, the measured initial value varied between 22 and 128 mm/10min with the higher values occurring in the dry season. Evapotranspiration as well as soil evaporation are slow mechanisms with values of around 10 mm/d. Based on these results, flooding caused by rainfall can only occur during heavy events which exceed the soil recharge capacity. The necessary amount of rainfall changes with the season and related soil pre-saturation. Assuming previous events have not saturated the soil, the water will infiltrate within a short time if not supported by additional rainfall or meteorological conditions which minimize evapotranspiration. Evaporation and evapotranspiration, while important in the long term, play a negligible role in the described short term processes.

4.4.2 Water budget of the floodplain areas

While sources of floodwaters may originate from both river and rainwater, results show that water levels on the floodplains fluctuate with the water levels in the swamps. In addition, soil water recharge and evapotranspiration outweigh rainfall quantities so that the source of larger scale area flooding can be established as river floods, while rainfall has a negligible effect. While river spill flows onto the floodplains, soil water recharge and evapotranspiration need to be considered which reduce the incoming flow quantities.

The general water budget in the rainfed grasslands, which receive water from rainfall only and not from river spill, is negative as shown in Figure 4.10. Recharge in the observation period during which typical rainfall events were observed reaches values of 60 to 70 mm. The saturation level of 350 mm is not reached as the water evaporates between rain events. Temporary rainfall flooding to a shallow depth may occur locally in the rainfed grasslands when strong rain events precipitate more water in a short time than can be infiltrated and consecutively evaporated by the soil.

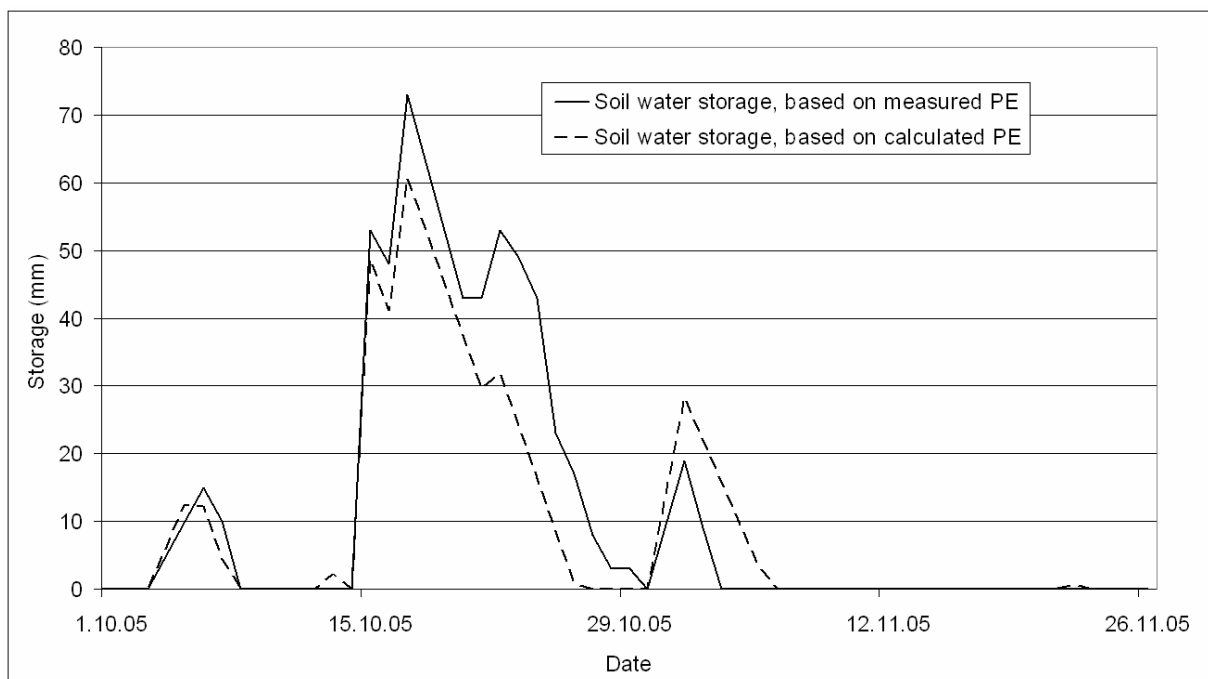


Figure 4.10: Soil water recharge in October and November 2005 based on rainfall data combined with measured and calculated evapotranspiration values. The point of soil saturation of 350 mm is not reached. Rain received before October has at this point already evaporated. The discrepancy between the two curves can be explained by measurement problems

The decline of floodwaters in the very shallow, widespread and densely vegetated seasonal floodplains has been investigated based on data collected during November 2005. Decreasing flood levels during this period have been measured with on average 5 mm/d. Water level differences between the grasslands and the main swamps (Figure 4.9) show that the levels in the swamps are continuously higher than on the flooded plains. This observation indicates that no return flow of flood water occurs from the plains into the swamp and that evapotranspiration processes can be held responsible for the receding of the floods. Soil test results show that percolation can be neglected as a factor for losses as after soil has recharged its moisture deficit, the highly impermeable ground conditions of the area do not allow further losses to lower permeable layers.

After the floodwaters have disappeared, evapotranspiration continues until soil moisture has dropped to a level where it can not support vegetation growth anymore. At this stage the grass is drying and eventually burns, the remaining water is evaporated by the soil. The indicative water budget for the river flooded grasslands is shown in Figure 4.11. A more detailed assessment was not possible as the inflowing floodwaters were not gauged.

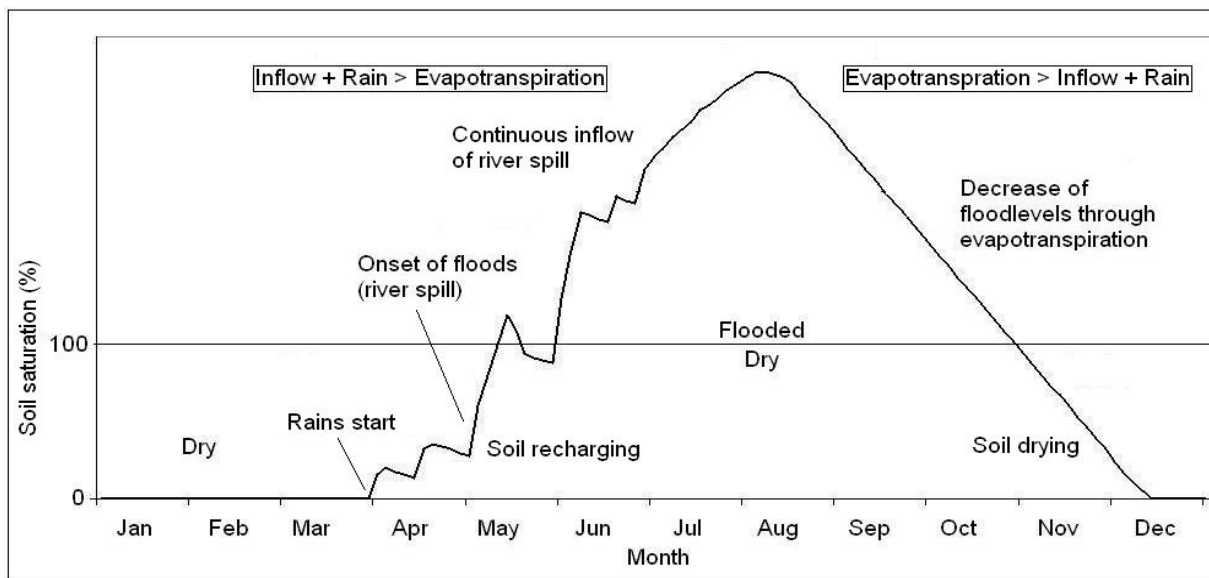


Figure 4.11: Indicative water budget of the seasonal flooded grasslands (riverfed) during an annual flooding cycle

4.5 Conclusions

Water budgets, flooding and drying mechanisms of the *toic* area, the seasonal flooded grasslands of the Sudd swamps between Bor and Shambe have been investigated. Findings show soil water recharge exceeding a maximum of 350 mm and evapotranspiration of 2075 mm/year. Deep percolation can be excluded due to impermeable soil conditions. Results of the soil water budget show that the soil in the rainfed areas does, during normal rain events and conditions, not reach its saturation point due to high evapotranspiration rates.

Floodwaters leading to permanent flooding originate from river spill, while rainfall may only cause temporary and shallow floods in exceptional circumstances during very intense rain events exceeding 77 mm/10min. Decreasing flood levels are caused by evapotranspiration processes while return flow into the river is negligible for the larger parts of the floodplains. Water levels, which are higher in the swamps than on the floodplains, highlight the significance of evapotranspiration processes at all times. It can be assumed that the loss of waters with the resulting gradients leads to a continuous uni-directional flow from the swamps towards the grasslands, a mechanism which may be important for sediment and nutrient transport.

Acknowledgements

Data for this work was partly collected through the South Sudan Road and Dike Rehabilitation Project (Petersen, 2006). John Sutcliffe's useful comments on a first draft and the support of the staff of the Department of Hydrology and Water Resources Management of the University of Kiel for the soil testing are acknowledged.

Chapter V - Estimation of ungauged Bahr el Jebel flows based on upstream water levels and large scale spatial rainfall data

G. Petersen, H. Bast and N. Fohrer
Advances in Geosciences (2008)
Submitted 15.01.08, Accepted 11.04.08, In Press

Abstract

The study derives Bahr el Jebel flow data at Mongalla, combining upstream flow from Lake Albert and torrential runoff derived from the Collaborative Historical African Rainfall Model (CHARM) rainfall data in the catchment between Lake Albert and Mongalla using GIS techniques. The results provide an updated rating curve for Lake Albert outflows and currently unavailable flow data at Mongalla, the entry to the Sudd swamp, with a high level of confidence for the period after 1983; data which are essential for detailed hydrological assessments of the swamp system with its significant importance for the economies and lives of people in the area.

Keywords: CHARM, Mongalla, Nile, torrents, Lake Albert, ungauged basins

5.1 Introduction

Mongalla, a town situated at the upper reach of the White Nile, here called the Bahr el Jebel, is the key gauging station for inflows into the Sudd swamps of southern Sudan, one of the world largest wetlands. Due to political instability, flow measurements have been suspended in 1983, leaving the inflow into the swamps ungauged. 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. The study area is shown in Figure 5.1.

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.

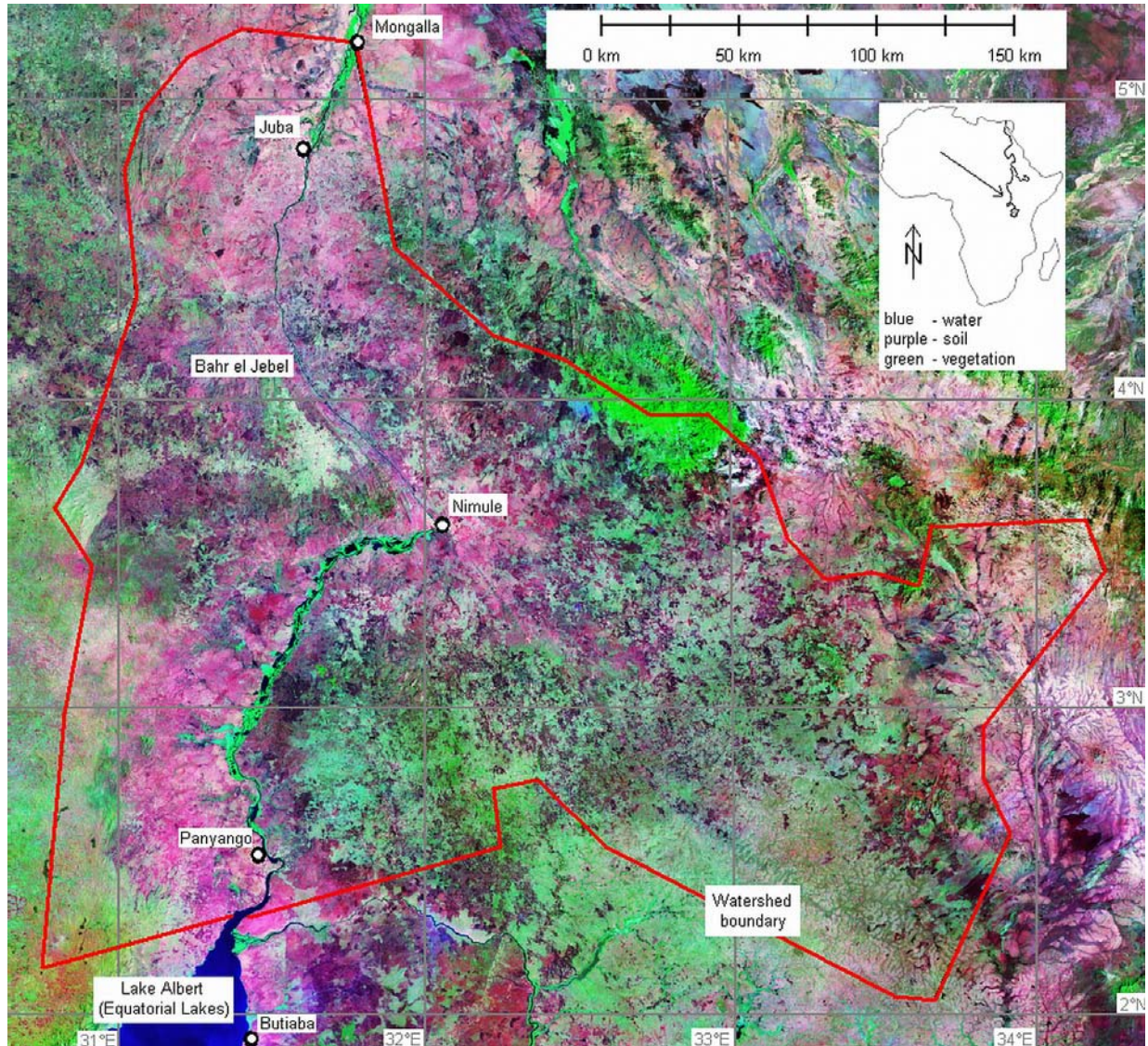


Figure 5.1: Area overview prepared from Landsat satellite imagery showing Lake Albert, the torrent catchment area and Mongalla gauging station. The Sudd swamps are located north of Mongalla, Lake Victoria is south of Lake Albert

JIT (1954) describe the flow reaching Mongalla, the gateway of the Sudd swamps, as being made up of two components, the discharge of the Equatorial Lakes and the torrential runoff from the upstream hilly areas. To capture the influence of the torrents, the area upstream of the Sudd swamps, namely the hilly area between Juba and Nimule as well as further upstream to Lake Albert, had to be considered. JIT (1954) showed that for average years the contribution from the Equatorial Lakes varies only from 1700 to $2000 \times 10^6 \text{ m}^3/\text{month}$. On the other hand, over the period from 1915 to 1919 the total flow at Mongalla averaged $3300 \times 10^6 \text{ m}^3/\text{month}$, while the torrents reached a monthly mean discharge of over $3000 \times 10^6 \text{ m}^3/\text{month}$ in September 1916 and over $4500 \times 10^6 \text{ m}^3/\text{month}$ in September 1917; values considerably higher than the corresponding lake discharges of 2000 and $2600 \times 10^6 \text{ m}^3/\text{month}$ respectively. In 1918 however the torrents never exceeded a monthly average of $400 \times 10^6 \text{ m}^3/\text{month}$.

This general picture highlights the importance of the torrential flows for the total discharges at Mongalla, which in turn would be important for any hydrologic analysis of the Sudd swamps. As Mongalla is a key gauge for understanding the processes in the Sudd, estimating the missing records is beneficial for any study in this area. The objective of this paper therefore is to estimate the important missing flow data at Mongalla from the two components of Lake Albert flow and torrent runoff. As the torrent flows are not gauged, they are deduced from spatial rainfall fields using the overlapping time periods where both Lake Albert outflows and Mongalla flows are available for calibration of the torrent flows. Lake Albert flows have been generated from lake levels measured at Butiaba utilizing newly generated rating curves. The paper describes how this work was carried out and evaluates the generated data for their suitability as base data for further hydrological assessments.

5.2 Methods

5.2.1 Study area description

The study area stretches for 438 km along the Bahr el Jebel from the exit of Lake Albert in Uganda to Mongalla in Sudan. The landscape is dominated by the river valley with the land rising into hilly terrain to the east and west. Rainfall in this area is highly seasonal and occurs in the rainy season between April and November yielding 943 mm annually. Vegetation cover, consisting of grass and acacia bushland, is varying with the season. Runoff discharges into the Bahr el Jebel through seasonal riverbeds. The catchment area between the exit of Lake Albert and Mongalla gauge which provides torrential runoff was determined using the USGS Geospatial Streamflow Model (Entenman, 2006). The 74,000 km² catchment area is shown in Figure 5.1; its typical features are shown in Figure 5.2.



Figure 5.2: Catchment area at Nimule. Looking west, Nimule is in the centre of the image and the distinctive right angle Nile bend is visible on the left

5.2.2 Approach to the problem and flow data sources

Data for locations within the area of interest are available for different periods of time as shown in Table 5.1. These datasets provide sufficient overlapping information to estimate missing periods of data based on correlation factors. Two overlapping periods were used for establishing these correlations. Panyango flows were used to calibrate calculated Lake Albert discharges, and combined Mongalla flow and rainfall runoff datasets for the period from 1961 to 1983 were used to calibrate and validate correlation coefficients for Mongalla (Hurst and Phillips, 1933), from which new flow data at Mongalla were estimated for the period from 1984 to 1996. Further estimating would be possible with additional rainfall datasets using the same principles.

Table 5.1: Availability of data for different locations

Year	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Lake Albert water levels												
Flow at Mongalla												
CHARM spatial rainfall												
Flow at Panyango												

Torrent flows were historically not directly measured but can be estimated by the difference between Lake Albert outflows and flows measured at Mongalla (Hurst and Phillips, 1938) using a principle as shown in Figure 5.3. As there is no permanent gauging station at the outlet of Lake Albert, outflows have to be deduced from a rating curve based on lake water levels measured at Butiaba and flows measured at Mongalla during the dry season (1). Losses through evapotranspiration and gains through dry season catchment runoff have to be taken into account with an estimated value of 5% of the Mongalla flows (Hurst and Phillips, 1938). The calculated Lake Albert outflow datasets (2) were validated with flow records measured at Panyango (3).

The rating curve for the Lake Albert discharges is altered by vegetation dynamics which in return are influenced by high or low flow conditions (Petersen et al. 2007). The curve was deduced by plotting monthly average Butiaba gauge readings against discharges at Mongalla for the dry season, split up into different periods of years which were selected according to significant flow conditions. The flows were validated with data measured at Panyango near the outlet of Lake Albert. For the White Nile at Mongalla, they provide dry season flows and base flows during the rainy season.

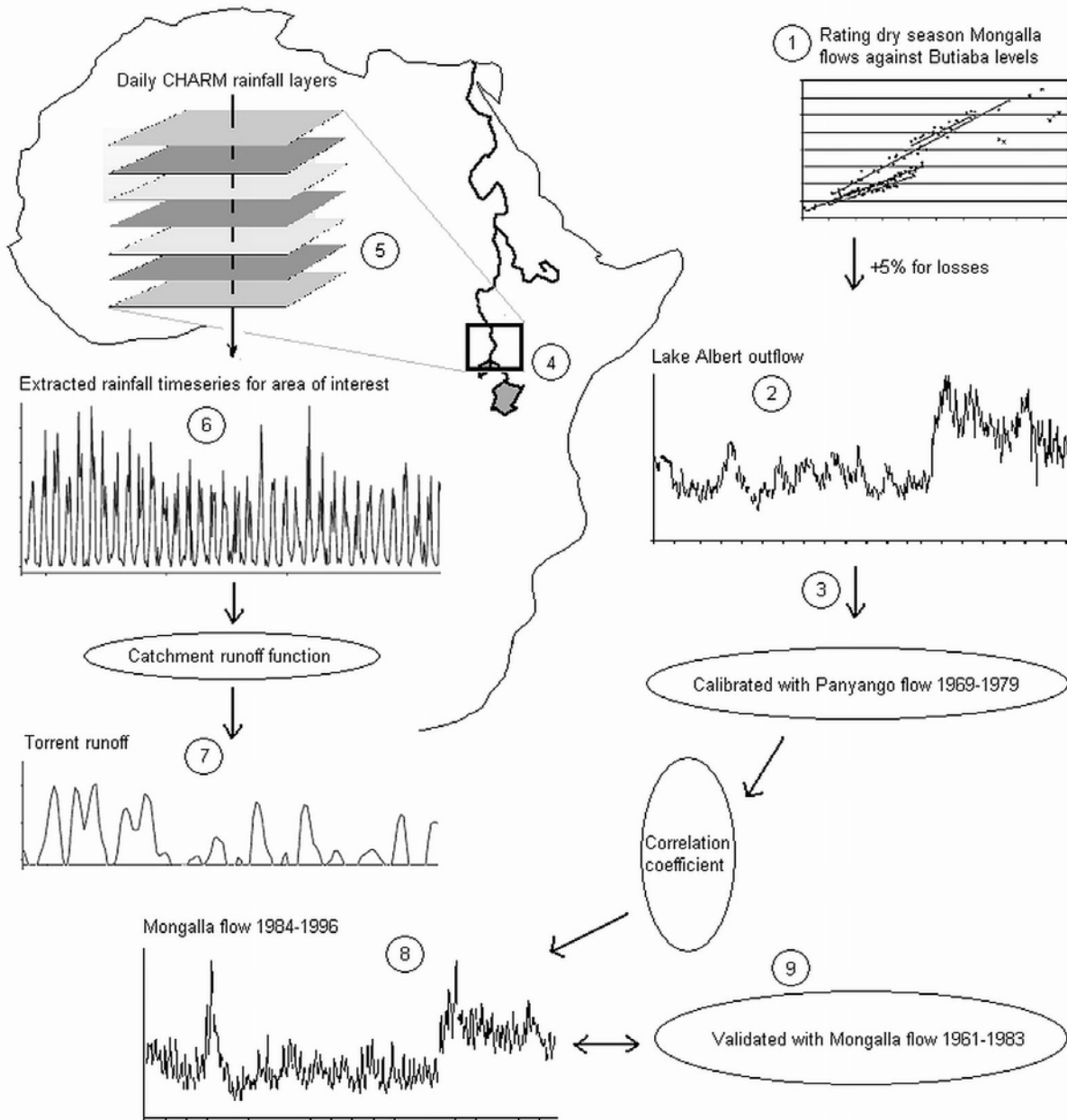


Figure 5.3: Principles of data processing and interactions utilizing timeseries (1-3) and spatial rainfall data (4-7) which are then combined (8-9) to calculate Mongalla flows.

5.2.3 Rainfall time series and torrent flows based on CHARM data

The rainfall data used in the analysis are based on CHARM data, a grid-based rainfall dataset called the Collaborative Historical African Rainfall Model which spans the time period 1961 to 1996 in daily resolution. The two key sources of data for CHARM are the National Centre for Environmental Prediction (NCEP) reanalysis time-series and station data. The daily estimated precipitation fields from the reanalysis are smoothed with a spatial filter (Funk et al., 2003).

This generates a set of 'synoptic' rainfall fields at a cell size resolution of 0.1 degree, equal to 11.2 km in the area of interest.

Based on the methodology shown in Figure 5.3, the rainfall data have been extracted from the CHARM grids for the catchment area between Lake Albert and Mongalla (4) for the period from 1961 to 1996. For the extraction of time series data from the daily spatial CHARM layers (5) a GIS tool was developed within the ESRI ArcGIS 9.2 (ESRI, 2007) environment using ArcObjects. The tool was built for a cell by cell extraction of daily rainfall values within a period of 36 consecutive years. The area of interest consists of 1224 single cells, which results in 421,575 values for one year and 15,186,700 values for the whole dataset (with some values missing). The tool extracts the values of all overlaying layers at a specific location for a specified cell. The data were analyzed calculating average, minimum and maximum values as well as the spatial distribution and extent of rainfall events resulting in an averaged rainfall time series for the area of interest (6). The values were then converted to runoff flow quantities (7) considering a runoff function to capture initial infiltration and losses which was derived through calibration with overlapping flow datasets using Equation 1. The power of 3 in combination with the reduction factor F_{red} simulates the non-linear behaviour of runoff caused by rainfall of different intensities including different relative infiltration rates and the degree of soil pre-saturation. For the calibration, the torrent flow was assumed to be the difference between flow at Mongalla and flow at Lake Albert outlet, i.e. Panyango less the estimated losses as described in Section 2.2.

$$Q_{torr} = Q_{rain}^3 \times F_{red} \quad (1)$$

With Q_{torr} = Torrent runoff quantity in the whole catchment ($m^3/month$)
 Q_{rain} = Rainfall quantity in the whole catchment ($m^3/month$)
 F_{red} = Reduction factor accounting for initial infiltration and losses

5.2.4 Estimating Mongalla flows

Adding Lake Albert discharges and the torrent runoff, the discharges at Mongalla were calculated (8). For calibration of the flows, overlapping pre 1983 datasets were used and a correlation factor applied to cater for damping effects. Assuming that the Lake Albert flows were sufficiently accurate, the flow data was calibrated in order to match the Mongalla flows when combined with the Lake Albert discharge for the overlapping period from 1961 to 1983 (9). The level of confidence in the estimated Mongalla flow data was established taking into account points of potential uncertainty including uncertainties in Lake Albert outflow, the CHARM data and the assumptions made in calculating the runoff using sensitivity calculations. Sensitivity trials have been conducted to gauge the effect of the different parameters in the overlapping period. The method was then applied to the post 1983 data to generate the Mongalla flow to 1996. For periods of missing Lake Albert records, outflow was estimated using linear interpolation, crosschecking qualitatively with outflow data from upstream Lake Victoria.

5.3 Results

5.3.1 Lake Albert outflow

Lake Albert outflows are based on a rating curve converting lake water levels at Butiaba into flows at Mongalla. These are assumed to be similar to those at Panyango (see Sect. 2.3). As the flows leaving the lake are sensitive to changing vegetation conditions which depend on high or low flows (Petersen et al. 2007), different rating curves have been established for the changing flow regimes in different years as shown in Figure 5.4.

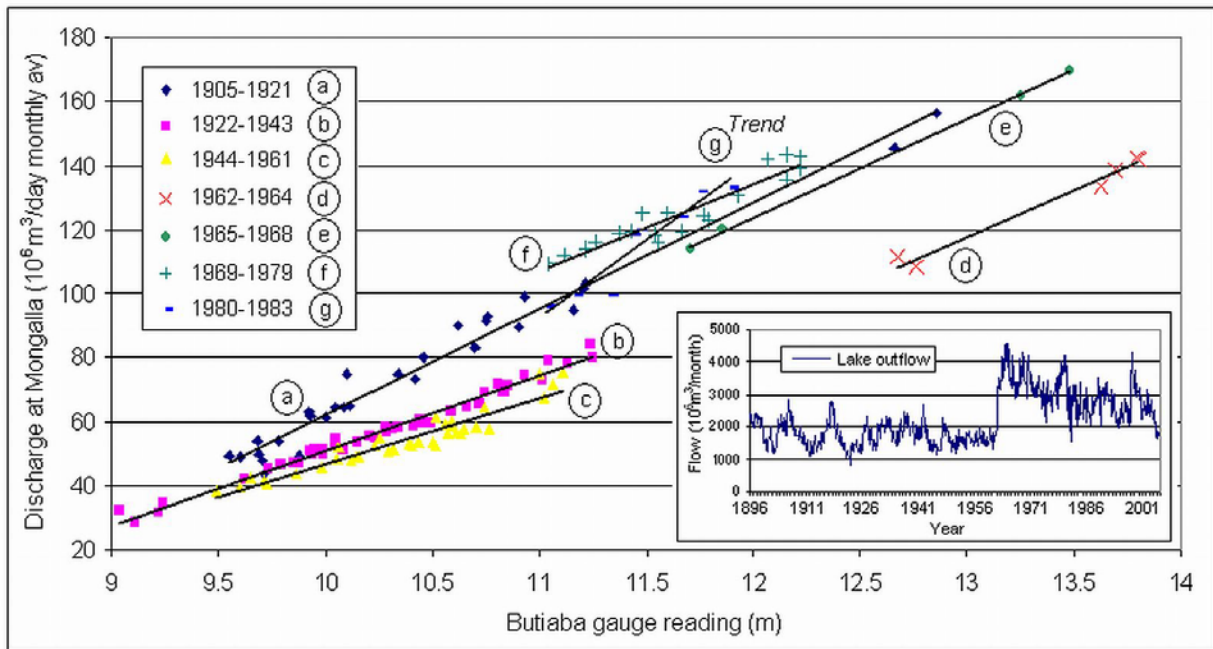


Figure 5.4: Dry season rating curves for Lake Albert outflow for periods with different typical flow conditions based on Lake Victoria outflow

The curves represent:

- a. 1905-1921 showing historical flow conditions
- b. 1922-1943 less flow leaves the lake as vegetation may have choked the exit of the lake during low flows in 1922
- c. 1944-1961 continuous low flow conditions and possibly vegetation growth lead to further decrease of outflow
- d. 1962-1964 very high flow events during this period lead to increased outflow
- e. 1965-1968 the rating curve has changed significantly due to opened up channels
- f. 1969-1979 comparatively higher discharges occur during this period
- g. 1980-1983 flows reduce, assumingly due to decreasing channel capacity with low flows allowing vegetation growth. The change in direction describes this trend

While no calibration data are available, it can be assumed that the trend of decreasing discharges continued after 1983 due to decreasing Lake Albert levels and related vegetation dynamics leading to a decrease of channel capacity. Based on the curves in Figure 5.4,

regression functions as shown in Table 5.2 were established. The resulting outflow data was compared with Panyango flow data for validation and shows good correlation as shown in Figure 5.5 and Table 5.3.

Table 5.2: Regression functions for dry season Lake Albert outflow for different periods as shown in Figure 5.4

Curve	Period	Regression function	
a	1905-1921	$y = 33.058x - 268.31$	(2)
a	1922-1943	$y = 23.363x - 182.66$	(3)
c	1944-1961	$y = 20.732x - 160.75$	(4)
d	1962-1964	$y = 28.980x - 258.68$	(5)
e	1965-1968	$y = 38.465x - 336.45$	(6)
f	1969-1979	$y = 53.696x - 515.202$ (calibrated)	(7)
g	1980-1983	$y = 68.519x - 691.114$ (calibrated)	(8)
h	1984-2004	$y = 63.625x - 650.985$ (calibrated)	(9)

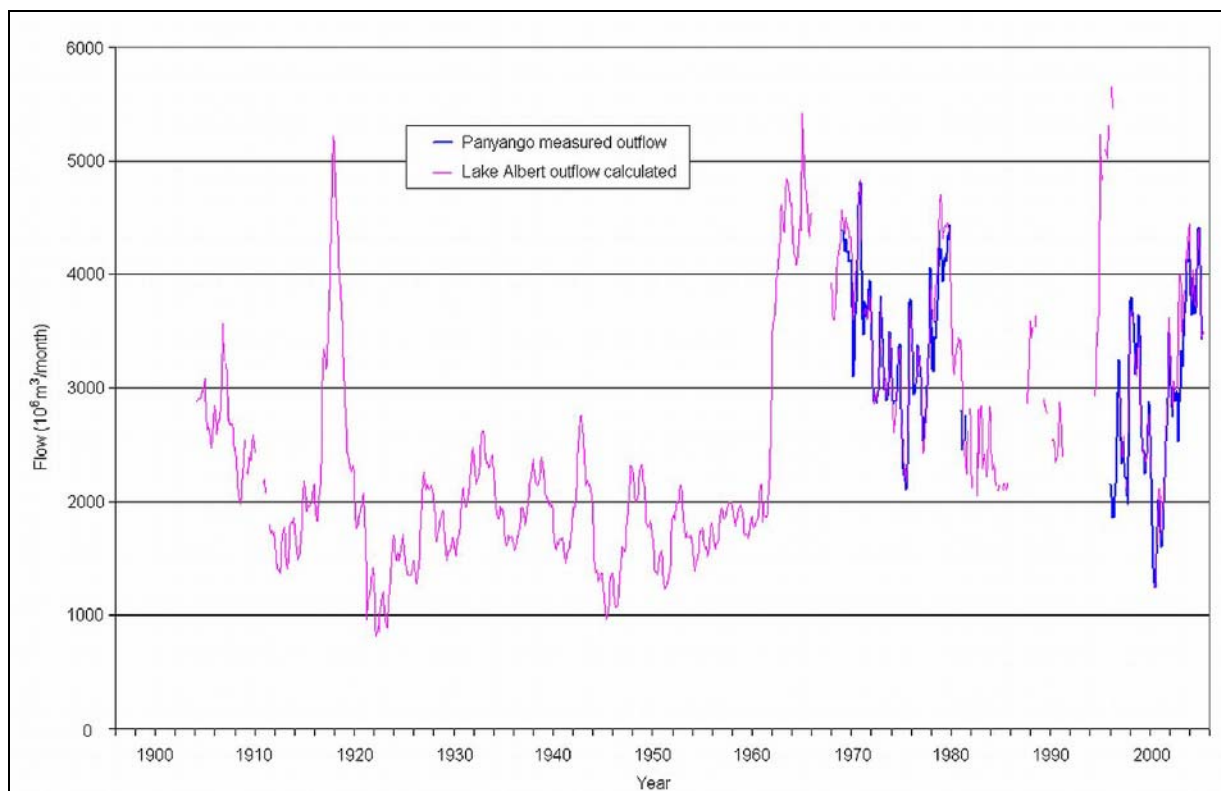


Figure 5.5: Comparison of calculated and measured Lake Albert outflow based on the relevant rating curve and calibrated using a correction coefficient, gaps are caused by missing input data

*Table 5.3: Statistical characteristics of Lake Albert outflow ($10^6 \text{ m}^3/\text{month}$) (mean, minimum, maximum, standard deviation, and correlation coefficient between measured and calculated values). The outflow was calculated from lake level readings with regression functions of Table 5.2 for the calibration periods *f* and *h* with available measured flow data at Panyango.*

Period	Mean	Min	Max	Std	R
1969-1979	3707	2106	4813	551	0.97
1996-2004	3418	1238	5062	896	0.96

5.3.2 Torrent runoff and Mongalla flows

Comparing the CHARM derived torrent flows with the flows derived from historical sources, good qualitative results were found during normal flow conditions while peak events were not captured sufficiently. The same result was found when comparing the calculated flows at Mongalla with measured values as shown in Figure 5.6. While qualitatively the time series are comparable, peaks during extreme events are not represented well by the modeling approach. A statistical analysis of the results is shown in Table 5.4.

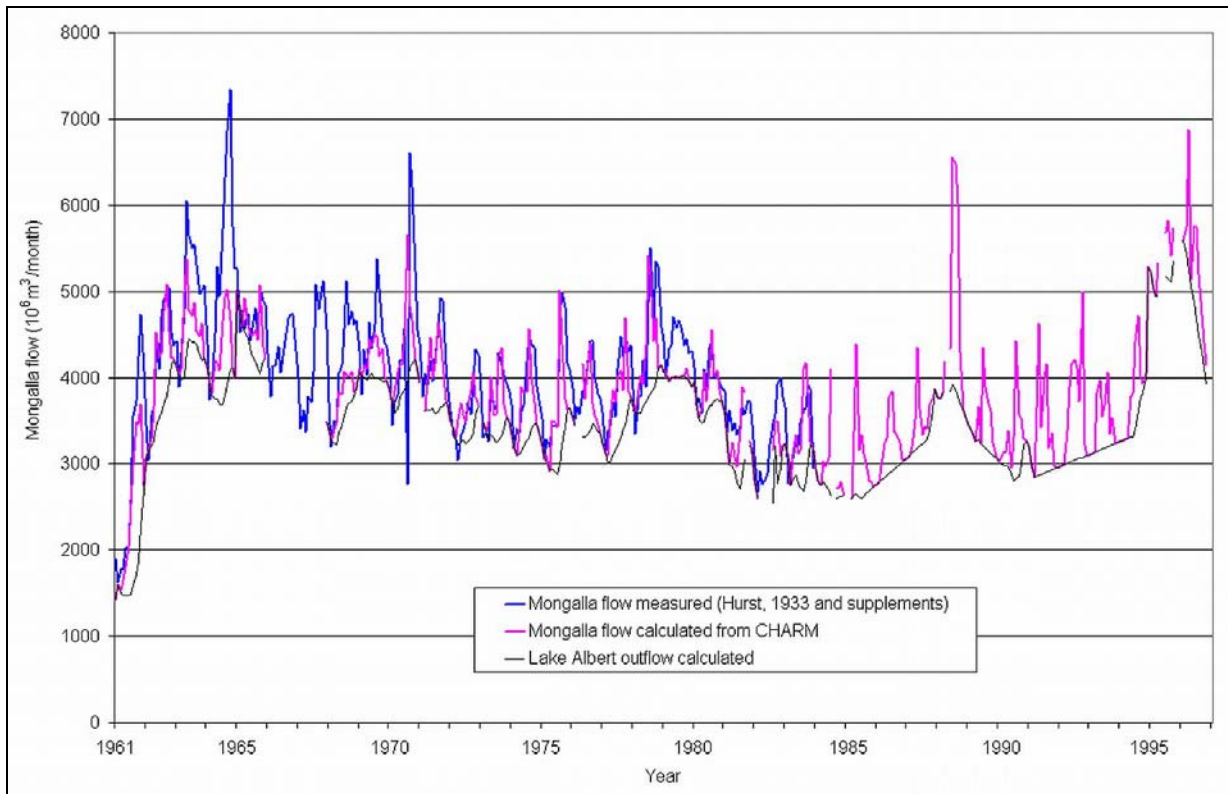


Figure 5.6: Comparison of calculated and measured Mongalla flows 1961 to 1983 as well as estimated Mongalla flows 1984 to 1996, gaps are caused by missing data, the baseflow from 1984 to 1996 is interpolated due to few available measurements

Table 5.4: Statistical characteristics of Mongalla flows (10^6 m³/month) (mean, minimum, maximum, standard deviation, and correlation coefficient between measured and calculated values)

Period	Mean	Min	Max	Std	R
1961-1983	3973	1426	7340	742	0.81

5.4 Discussion

Evaluating the quality of results obtained in the assessment of Mongalla flows from CHARM data compared to measured data as shown in Figure 5.6, the results prove to be of reasonable quality, showing a correlation coefficient of $R = 0.81$, the mean deviation was calculated with 4.4 %. For the estimated Mongalla flow time series from 1984 to 1996 it has to be taken into account that part of the Lake Albert flow data are interpolated and that, while Lake Victoria outflows which have been compared for this time period confirm the trends, fluctuations in Lake Albert flow are neglected. The obtained Mongalla flows for the 1984 to 1996 period are judged as a reasonable representation of real conditions considering the above statistics and the comparable low fluctuations of Lake Albert outflow.

Considering the spatial approach to estimate runoff quantities from rainfall in the area it has to be taken into account that rainfall events in reality are highly localized while averaged in this study. The derived runoff function can therefore be assumed to underestimate runoff if applied to smaller sections of the catchment area. For the assessed large area anyhow, representative results have been achieved.

5.5 Conclusions

Flow records derived from spatial rainfall datasets and lake level time series have been successfully estimated for an ungauged section of the Bahr el Jebel catchment. The results provide a near reality flow time series extending the available Mongalla data for the period from 1984 to 1996. This time series could be further extended using additional available spatial rainfall data. The derived Mongalla flow data will be important for future modeling tasks in the Sudd region for which Mongalla is the key inflow gauging station.

Chapter VI - Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan

G. Petersen and N. Fohrer
Hydrological Sciences Journal
Submitted 02.04.08

Abstract

A two-dimensional hydrodynamic assessment of the Nile swamps in southern Sudan has been carried out using DHI MIKE 21 software based on a ground referenced and corrected Shuttle Radar Topography Mission (SRTM) digital elevation model. The model was set up and calibrated using available historical information as well as newly measured data. Results show the model capable of representing the hydraulic conditions in the swamps, allowing the assessment of different flow conditions and their effects on the swamp. The study has established water level gradients, flow directions and velocities in the swamp as well as on the seasonal floodplains and describes the importance of evapotranspiration for losses in the system.

Keywords: Swamp model; Sudd; Floodplain

6.1 Introduction

The Sudd swamps of southern Sudan, one of the largest wetland areas in Africa, are defined by seasonal flooding and are responsible for the loss of large quantities of the inflowing waters of the White Nile, here called the Bahr el Jebel. Evaluating flow data from Hurst (1933 and supplements), approximately half of the inflowing waters are lost between Mongalla and Malakal, the respective entrance and exit of the swamp system.

Historical information about the region is mainly available from studies carried out during the last century. Hurst & Phillips (1931, 1938) and Butcher (1938) were the first to carry out intensive research in the Sudd swamps describing hydro-meteorological conditions. Shrinking and swelling of the Sudd soils was investigated by Migahid (1948). The Jonglei Investigation Team (JIT) (1954) mapped the soil types of the Sudd and defined the area in the immediate vicinity of the swamps as *sudd* or *toic* soils. Mefit-Babtie (1983) collected humidity, sunshine and temperature data during the Jonglei Canal studies at Bor and Malakal, and described the seasonal cycle of water-logging and desiccation leading to deep cracking of the soil. Wright, in JIT (1954) gave initial hints on soil water recharge assuming values between 300 and 800 mm, assuming that the latter was overestimated. Sutcliffe (1974) described the vegetation distribution of different species in the swamps and Petersen *et al.* (2007a) described the

vegetation dynamics with regard to changes in the permanent swamps. The influence of the area morphology on flooding was described by Petersen *et al.* (2007b) evaluating flooding conditions in local depressions.

The Sudd has been described using different mathematical (Sutcliffe & Parks, 1987) and numerical (Mohamed, 2005) approaches. While these models give a good overview of the system, a comprehensive analysis of the hydrodynamics and water balances of the swamp and floodplains with consideration of all involved factors is not available.

The swamps and floodplains are important features of the area in terms of their ecological and economic value. A detailed knowledge of their function and a full understanding of the system are important for any future planning tasks. The objective of this paper is the investigation of the detailed processes and mechanisms in the swamps and floodplain flows, describing the hydrodynamics under different flow scenarios. Specific objectives include the assessment of flow velocities, water depth and individual flow patterns in the swamps and on the floodplains as well as an evaluation of interdependences.

6.2 Materials and methods

6.2.1 The study site

The study site stretches from Mongalla, the upstream entrance of the Sudd swamps, to a line north of Shambe in the centre of the swamps covering an area 130 km x 220 km West to East and South to North respectively, as shown in Figure 6.1.

The area has a changing topography as described by Petersen *et al.* (2007b) with the river meandering within an incised trough between Mongalla and Bor, and heading into an unrestricted floodplain area between Bor and Shambe where ground slopes average 1/10,000 from south to north. DEM analysis shows that north of Bor the river forms an inland delta and flows on an elevated ridge (Petersen *et al.*, 2007b), laterally not restricted by banks but by permanently inundated vegetation, mostly papyrus and reeds as shown in Figure 6.2. These swamps contain varying numbers of multiple river channels and lagoons. Depending on flow and wind conditions, parts of the papyrus fields can become dislodged and can block channels leading to a highly dynamic system (Petersen *et al.*, 2007a). Flow within the reed fields has been estimated as 7% of the cross sectional flow in the permanent swamp area (Petersen *et al.*, 2007b).

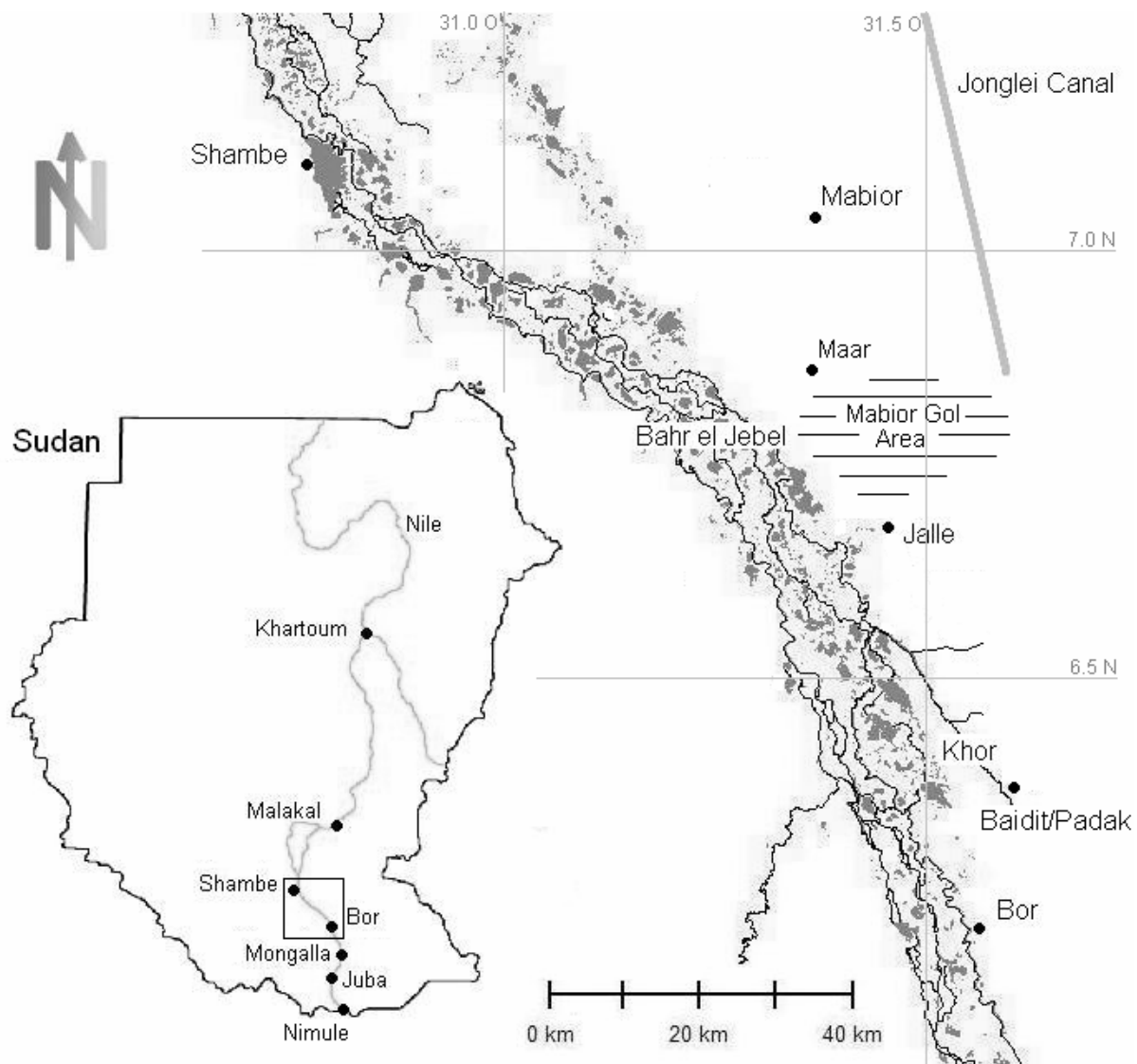


Figure 6.1: Overview of the assessment area; the model was set up between Mongalla and Shambe, the image shows main channels and lagoons in this area. The core area of interest, which has been assessed in detail, is located on the right bank between Baidit/Padak and Jalle



Figure 6.2: Papyrus - dense swamp vegetation with a height of typically between 3 and 5 m

The water levels within this vegetation are controlled by lateral spill from the river as well as resistance to flow and evapotranspiration in the vegetation. The spill feeds into this vegetation with water levels declining from the river towards the floodplains, the slope being shaped by flow restriction through reeds and evapotranspiration processes. A schematic sketch is shown in Figure 6.3.

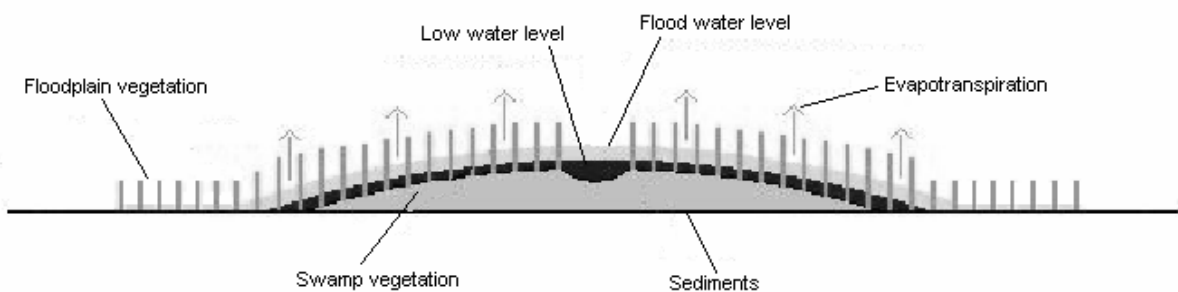


Figure 6.3: Schematic cross section of the Sudd swamps north of Bor

The edge of the permanently inundated swamp area is marked by the transition between swamp vegetation and grass species. The system is dominated by the annual cycle of flooding

and drying controlled by changing inflows based on discharges from the Equatorial Lakes, heavy local rainfall and evapotranspiration. In the rainy season the river level rises and spill increases which leads to a general rise in water level throughout the system, causing spreading inundation of the seasonal floodplains. With the start of the rainy season, the grasses on these plains grow quickly and are always higher than the water level, causing high resistance to flow. These grasses dry after the end of the rains and when flood waters have evaporated. The residues are typically removed by bushfires. With the onset of the rains, vegetation growth on the floodplains starts again.

The soils of the Sudd region are typical African floodplain black cotton soils with high clay content, classified as Vertisols (IUSS Working Group WRB, 2006) which in the dry season are heavily cracking. The layers below consist of impermeable clay which extends to a depth of 12 to 20 m followed by sandy material (Petersen & Fohrer, 2008).

6.2.2 Hydrological conditions

Hydrological conditions in the area are controlled by the outflow from the Equatorial Lakes and the torrent runoff in the area between these lakes and Mongalla (Petersen *et al.*, 2008). Within the swamp, flows are not sufficiently gauged to describe the whole cross sectional flow, but water levels measured at different locations give a good overview of the conditions under different flow regimes (Figure 6.4). The long-term quality of the data has been assessed based on their stage-discharge relation over time.

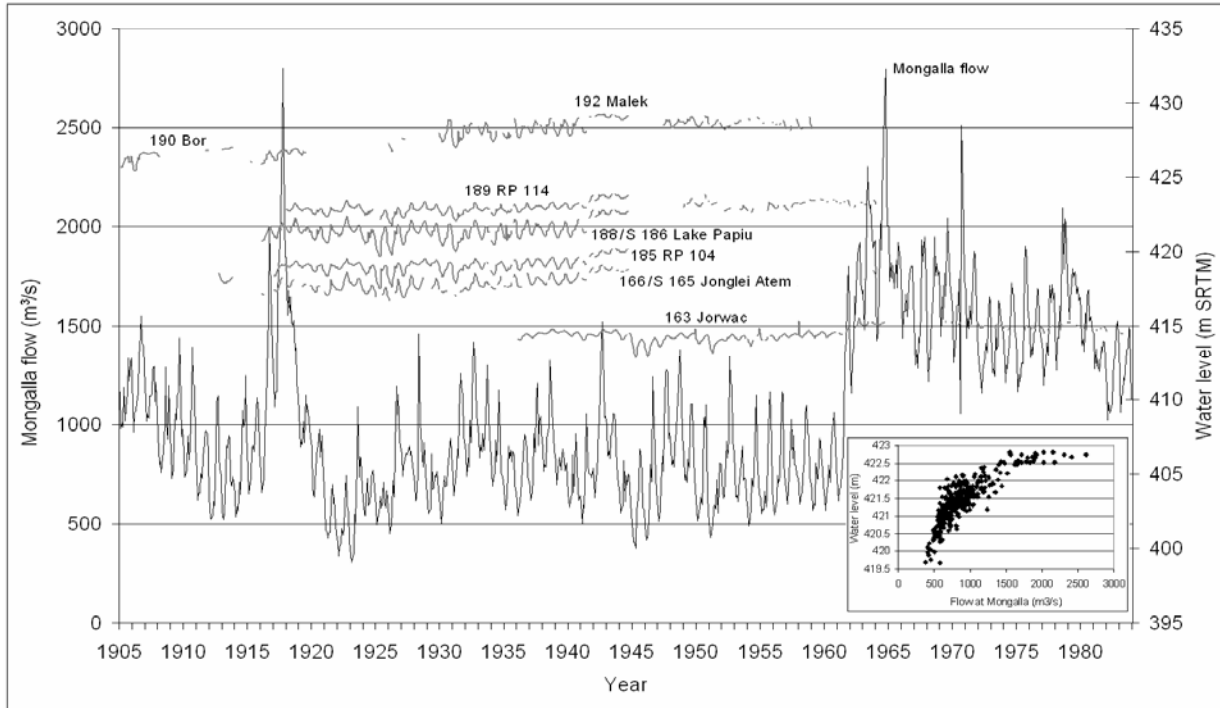


Figure 6.4: Flows at Mongalla and water level records, corrected to SRTM levels, at different locations in the southern Sudd swamps derived from Hurst & Phillips (1932 and Supplements). Flows and levels are directly related as shown in the inlay. The locations of the numbered stations are shown in Figure 6.5

Soil water recharge is an important process in the area. After the dry season, the soils recharge up to 350 mm of water before becoming impermeable and allowing flooding to take place (Petersen & Fohrer, 2008). A defined rainy season can be observed between April and October with a long-term average of 847 mm of annual rainfall. Yearly evapotranspiration in the swamps averages 2075 mm with up to 20 mm/d (Petersen & Fohrer, 2008).

6.2.3 The DHI MIKE 21 model

MIKE 21 (DHI, 2008) is a professional engineering software package for the simulation of flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas and seas. The full time-dependent non-linear equations of continuity and conservation of momentum are solved by implicit finite difference techniques with the variables defined on a space-staggered rectangular grid. The Hydrodynamic module simulates the water level variations and flows in response to a variety of forcing functions in the flood plain. It solves the vertically integrated equations for the conservation of continuity and momentum, i.e. the Saint Venant equations on its rectangular grids covering the area of interest, provided with the bathymetry, bed resistance coefficients and boundary conditions. The effects of sources and sinks like soil water recharge, precipitation and evaporation, river discharge and intakes are included in the hydrodynamic equations.

6.2.4 Model setup, sensitivity and calibration

The model was set up using a corrected SRTM (Shuttle Radar Topography Mission) DEM (NASA, 2006a) with channel and lagoons digitized from Landsat (NASA, 2006b) images imprinted into the DEM. The DEM was furthermore evaluated and corrected to represent an appropriate channel and lagoon network as well as realistic surface elevations in the densely vegetated areas where the SRTM would exaggerate ground elevations (Hofton *et al.* 2006). The model area was meshed using a 100m rectangular grid.

Two open boundaries were defined over the respective full cross section of the swamp with the upstream boundary at Mongalla controlled by inflow and the downstream boundary near Shambe controlled by water level. Average daily evapotranspiration was set as 0.07 m; flooding and drying depth was set to 0.35 and 0.1 m respectively with the flooding depth representing an assumed soil water recharge value of 350 mm (Petersen & Fohrer, 2008). These values were varied depending on the nature of the different scenario runs. Roughnesses were set using a map file representing water bodies, permanent swamp area and seasonal flooded grasslands based on recommendations of the Conveyance Estimation System (Wallingford Software Ltd. 2006). Results were recorded at defined locations within the swamp area (Figure 6.5) for which data from monitoring stations were available to compare simulated with measured values under comparable steady state flow conditions. In addition, spatially distributed result were generated and evaluated for a core area between Baidit/Padak and Jalle where most accurate calibration data were available (Petersen, 2006). The model area with the enlarged core assessment area is shown in Figure 6.5.

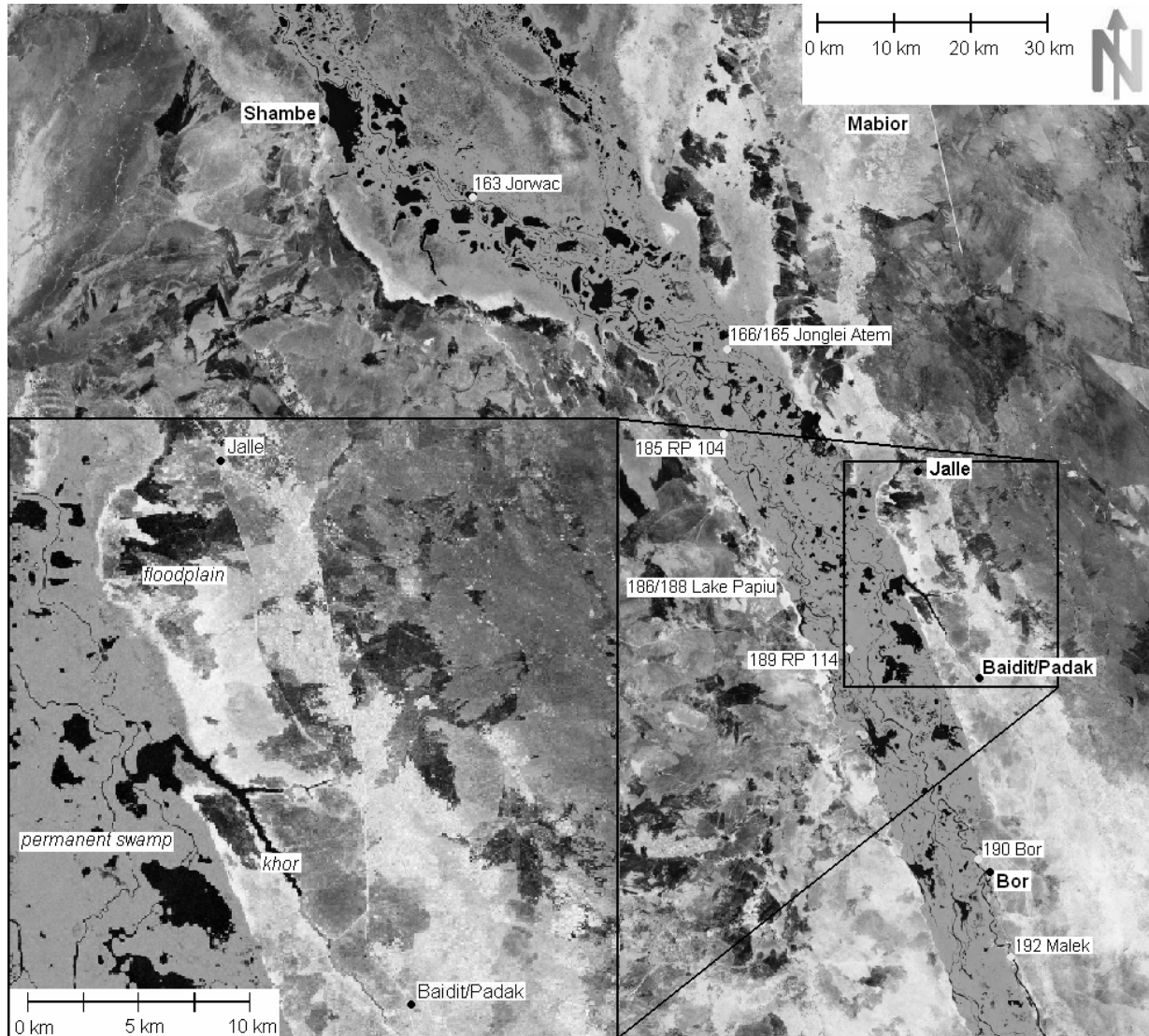


Figure 6.5: Dry season Landsat image of the model area showing the swamp with monitoring station numbers and locations as well as the enlarged core assessment area between Baidit/Padak and Jalle.

A wide range of resistance values have been tested. Final Manning values (n) of 0.01, 0.11 and 0.20 were selected for the watercourses, papyrus fields and floodplains respectively. Vegetation dynamics (Petersen *et al.*, 2007a) have been neglected in the assessment. Sensitivity analyses were carried out to test the model behavior for a range of individually tested parameters as shown in Table 6.1. Findings of these analyses were used to tune the model in a calibration process and also to estimate the level of confidence in the model results. In addition the effects of precipitation and evapotranspiration on the flood patterns were tested to determine their significance.

Table 6.1: Sensitivity parameters

Parameter	Description	Range	Unit
Bathymetry	correction	-0.5/-1.0/-1.5	m
Boundary	upstream inflow	400-2800	m ³ /s
	downstream elevation	412-416	m (SRTM)
Resistance	water bodies	0.005-0.02	n (Mannings)
	permanent swamp	0.05-0.33	n (Mannings)
	seasonal grasslands	0.05-1.00	n (Mannings)
Soil water recharge	flooding depth	0-0.4	m

Boundary conditions for representative scenarios and tuning parameters were then combined to calibrate and validate the model using historical measured data for defined high and low steady state flow conditions. To assess changes in flow directions and velocities, batched inflows relatively higher and lower than the initial conditions were simulated to observe changes in the system and with special interest in the floodplain flow conditions.

6.3 Results

Sensitivity runs show that the bathymetry correction and roughness parameters have a controlling influence on the performance of the system. Results indicate that:

- Bathymetry settings to compensate for the exaggerated representation of ground elevation of the SRTM data for water bodies and vegetation have an important influence on the system. The papyrus fields were found to be well represented after a correction value of in average -0.8 m was applied. Due to a lack of ground reference points in the downstream model area, the DEM data has proved unsuitable for detailed assessments there
- Inflow has a direct influence on the system and, in combination with the DEM correction and roughness, is the main factor for the distribution, extent and depth of inundation in the swamps and on the floodplains. Downstream water levels on the other hand have no effect for most of the upstream system while they control inundation depth and extent in the vicinity of the downstream boundary
- Flooding depth settings were successfully used to simulate soil water recharge effects neglecting the first 0.35 m of flooding without allowing for permanent infiltration
- Evapotranspiration has a visible influence on the spread of flooding over time and in regulating the flood extent
- Precipitation and the influence of this parameter for the system has been found negligible for normal cases while extreme events show short term effects in area flooding
- Flow resistance is a main tuning parameter for calibration to which the model reacts very sensitive

The calibrated model shows a qualitatively realistic behavior generating natural water levels under the modeled low flow dry season and high flow rainy season scenarios as shown in the

calibrated model results for the Baidit/Padak region in Figure 6.6 and 6.7. The flood extent is limited to the permanent swamp boundaries in the dry season and covers the floodplain area in the rainy season. Modeled water depths on the floodplains during inundation reach values of up to 1.2 m.

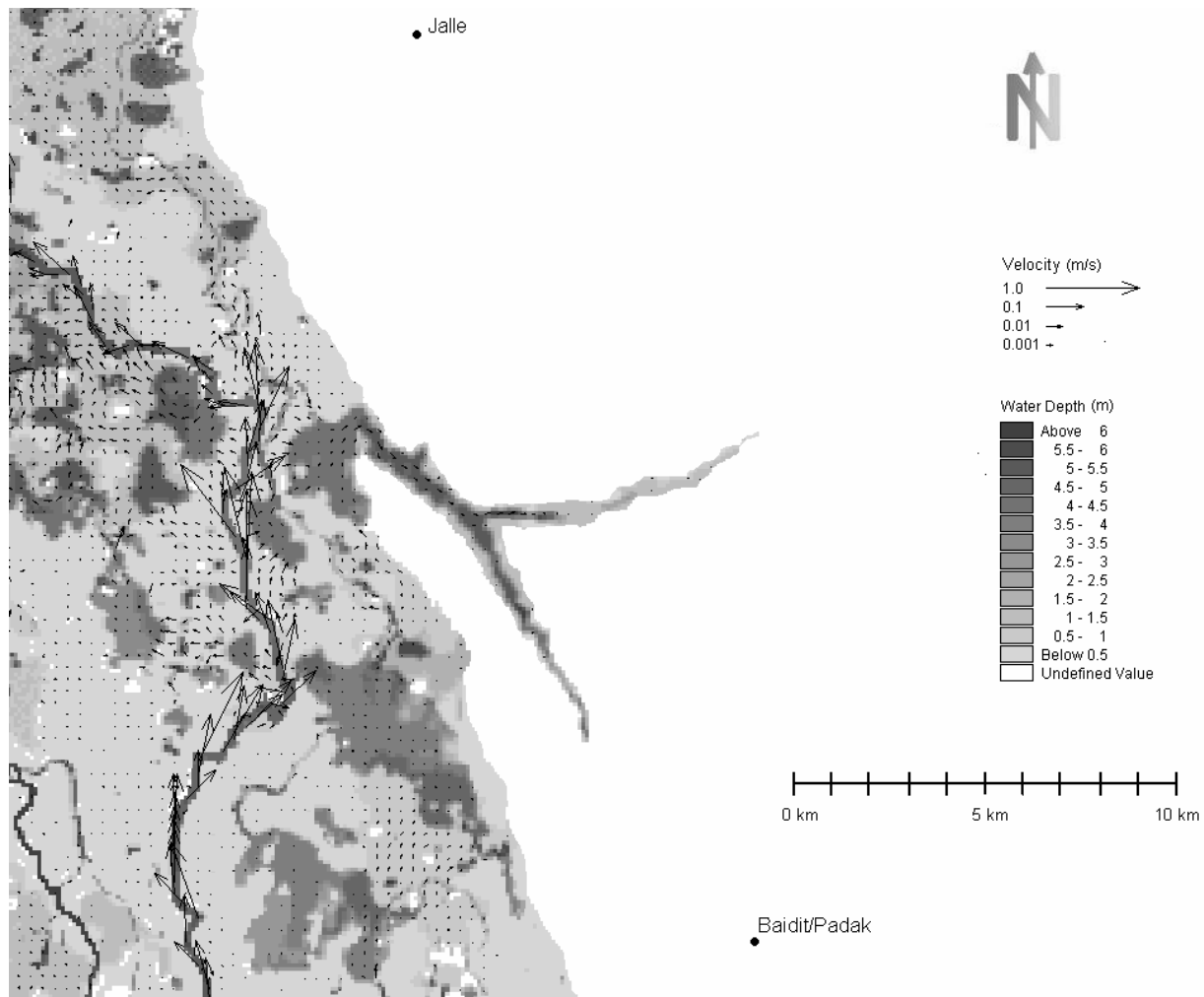


Figure 6.6: Water depth, inundation extent and velocities under typical dry season low flow conditions ($1000 \text{ m}^3/\text{s}$ swamp inflow at Mongalla). While the channel flow velocities are well visible, flow velocities within the papyrus areas are hardly visible due to their small values

Velocities and flow directions resulting from the model runs have been assessed at different locations in the channels, swamp vegetation, khors (shallow depressions that lead inland from the swamps) and on the floodplains under different flow conditions. Model results show flows of up to 1.5 m/s and average of 0.6 m/s in the channels, while flows in the swamp vegetation and on the floodplains are limited to on average 0.005 m/s. Flow directions on the seasonal floodplains, assessed with runs simulating increased as well as decreased inflow, show a continuous flow pattern in downstream direction over the plains (Figure 6.6 and 6.7) but no return flow into the swamp even under decreasing boundary inflow conditions. This situation is related to the water levels generally sloping away from the swamp towards the floodplains.

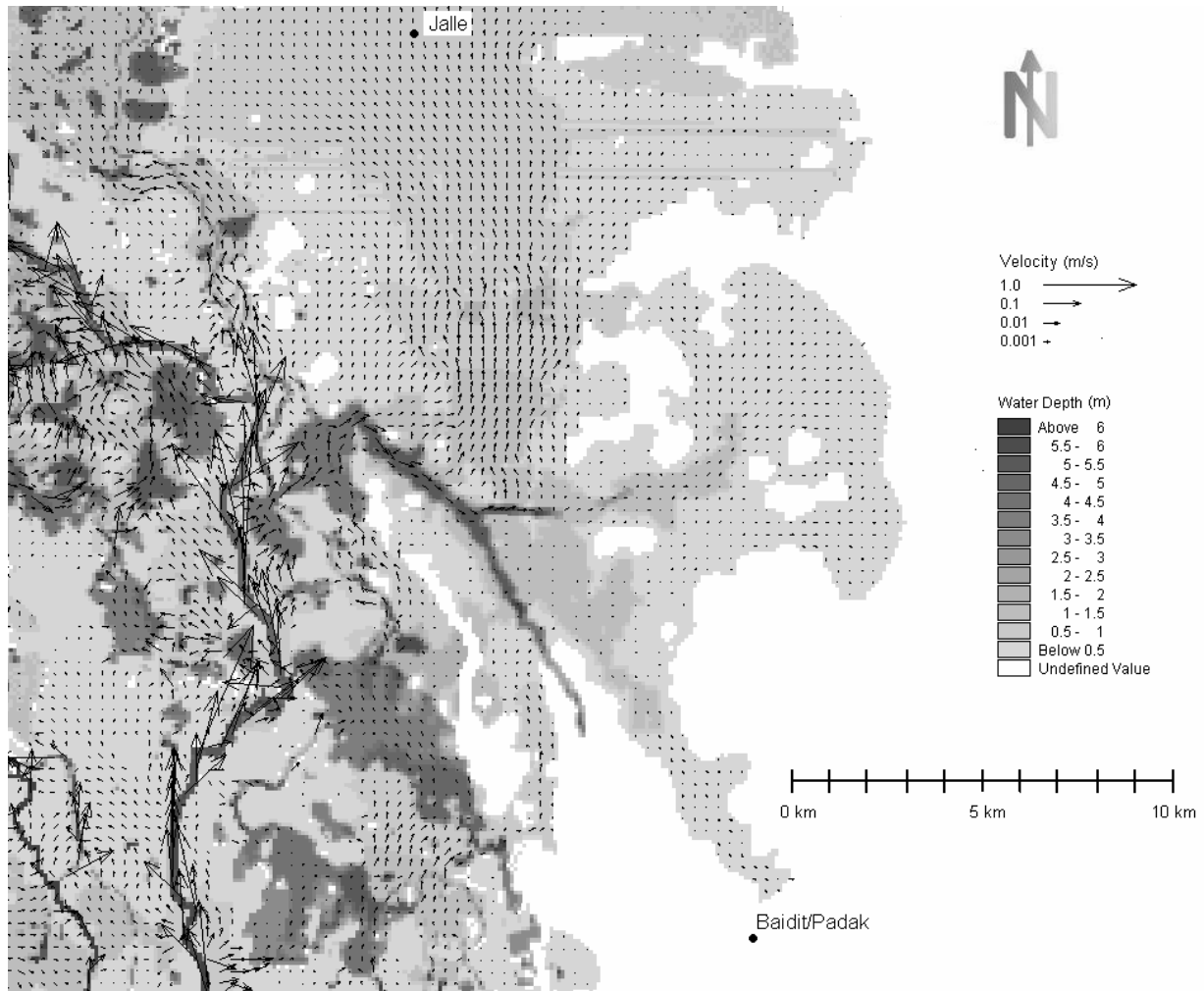


Figure 6.7: Water depth, inundation extent and velocities under typical rainy season high flows ($2000 \text{ m}^3/\text{s}$ swamp inflow at Mongalla) in the core assessment area. Water is flowing down the seasonal floodplains which are inundated under these conditions

The same finding was made for water levels and flows in the khors, where water levels are sloping away from the swamp as well under all assessed conditions. The onset of flooding including water levels on the floodplains is dependent on exceeding an inflow threshold into the system at Mongalla with a relation as shown in Figure 6.8.

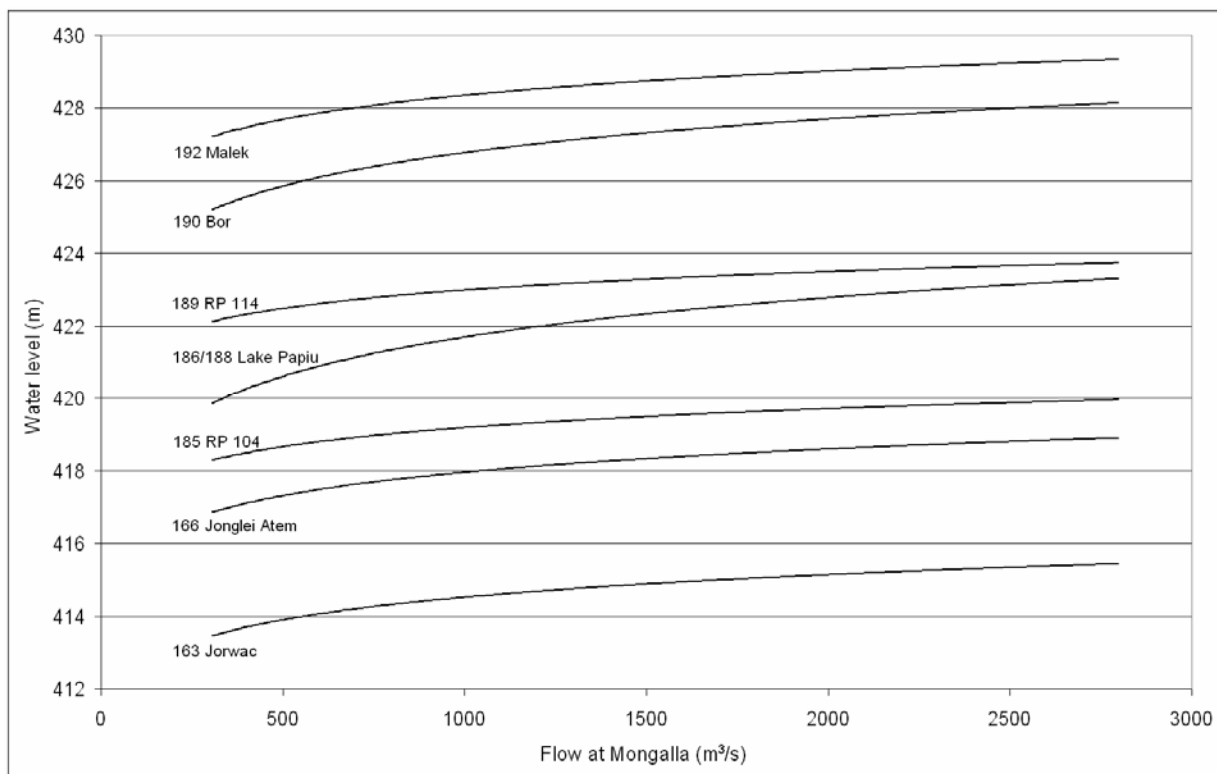


Figure 6.8: Inflow-level relation for different station locations in the model area as shown in Figure 6.5. The curves may vary depending on the long-term flow regime with related vegetation dynamics. Station names are given together with the respective station numbers

6.4 Discussion

6.4.1 Model performance

The model performance and ability to simulate the above scenario has been assessed comparing modelled to measured parameters including velocities, flow directions and water depth. Model results for the channels show average velocities of 0.5 and 0.8 m/s for dry season and rainy season conditions respectively. These velocities are within the expected range and are confirmed by measured velocities of on average 0.47 m/s, measured during a dry season field campaign in 2005/2006. Modeled velocities within the papyrus and reed areas show values of 0.001 to 0.01 m/s, flowing towards the floodplains. These values are comparable to measured velocities of 0.0 to 0.1 m/s (average 0.003 m/s).

Water levels and flood extent generated by the model under the modeled low flow dry season and high flow rainy season scenarios show a realistic behavior and compare well to observations made in a 2004 - 2006 field campaign. Both water levels in the swamps as well as flood extent, the latter being assessed only qualitatively, were represented as shown in the calibrated model results for the Baidit/Padak region in Figure 6.6 and 6.7. Modeled water depths on the floodplains during inundation also compare well to measured values of up to 1.2 m, measured during the same period. Water levels within the system are directly related to

different inflow conditions at Mongalla, with vegetation dynamics causing local changes. The threshold value for the onset of area flooding can be assumed to vary depending on the long-term flow regime with its related vegetation dynamics (Petersen *et al*, 2007).

Qualitatively assessments show levels sloping away from the main channels under all conditions, reflecting natural conditions. This situation results from the high evapotranspiration rates in the papyrus fields and on the floodplains leading to a steady flow into these loss areas.

6.4.2 Seasonal floodplain flows

The Sudd swamps can be divided into channels, lagoons, vegetated swamp and seasonal floodplains with different hydraulic conditions. While the model performance was confirmed by comparing the results for areas within the permanent swamp with measurements, flow patterns in the seasonal floodplains were unknown and had so far only been assessed by comparing water level differences leading to suggestions that flows are unidirectional and waters entering the floodplains do not return to the swamp during low water periods but maintain on the floodplains until evaporated (Petersen & Fohrer, 2008).

Model results (Figure 6.7) confirm this general picture and show that the inflow towards the floodplains occurs along a water level gradient from the main channels through side channels and lagoons as well as khors. Model results show no return flows under decreasing inflow conditions at Mongalla and the general water level gradient from the channel towards the swamp is, while varying in slope, maintained under all assessed conditions as shown in Figure 6.9. The discrepancy between measured and modeled values may be explained with slight inflow differences and different vegetation conditions. As described, the same condition applies for the khors, leading to the conclusion that the khors function is to convey water from the swamps inland, contributing to floodplain flooding, but not to allow runoff to drain from the floodplains into the swamp.

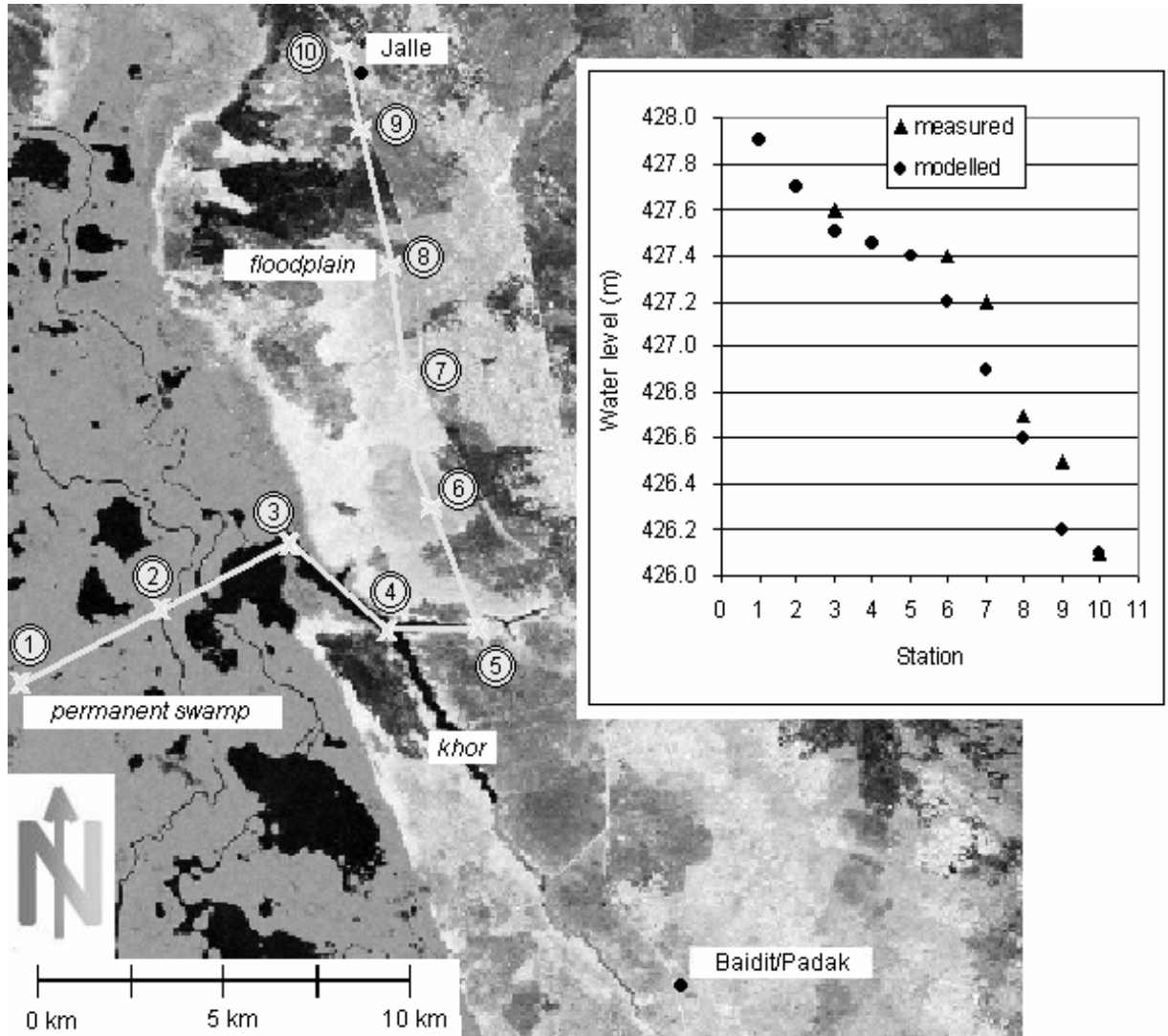


Figure 6.9: Modeled and measured water level gradient along a line from the center of the swamps through lagoons and khors onto the seasonal flooded grasslands under rainy season average high flow conditions ($2000 \text{ m}^3/\text{d}$ at Mongalla). The Landsat background image shows dry season conditions for better visualization

6.4.3 Components of flooding cycle

While groundwater interaction has not been assessed, assuming it to be negligible due to the impermeable clay soil conditions (Petersen & Fohrer, 2008), the elements of soil water recharge, precipitation, evapotranspiration and floodwater inflow have been assessed with the model. Soil water recharge was found to have a significant effect on the flooding pattern. The effect is altered by precipitation which may have a strong influence on soil water recharge depending on intensity and the timing before the inflow of floodwaters from the swamps. Flood water inflow, overlaid by evapotranspiration, has the most significant influence on area flooding (Figure 6.7) and is directly related to Mongalla flows as shown in Figure 6.8.

6.5 Conclusions

A 2D numerical model has been set up to assess the Bor-Mabior area of the Sudd swamps in southern Sudan. Based on comparisons with measurements and observations, the model has been found capable of representing the hydrodynamic conditions in the area and was successfully used to assess the flow patterns on the seasonal flooded grasslands. Main findings of the modelling work include:

- The corrected SRTM DEM is a good representation of the topography of the core area of interest for which a sufficient number of ground control points and vegetation information were available. For the downstream areas which could not be corrected due to a lack of ground control points, the SRTM accuracy could not be assessed but questionable model results for this area indicate a low level of confidence
- Water level gradients in the permanent swamp area and the khors have been established as sloping away from the main channels towards the floodplains under all assessed conditions. This leads to a permanent flow away from the channels into the swamp and, at high water levels, onto the floodplains. Waters that enter the floodplains do not return to the swamps but are lost by evapotranspiration
- Modeled flow velocities in the channels, the papyrus swamps and on the floodplains have been established for a range of conditions, showing values of 0.5-0.8 m/s, 0.001-0.01 m/s and 0.001-0.006 m/s respectively. Measured values of 0.47 m/s and 0.0 to 0.1 m/s for the channels and papyrus areas respectively confirm the quality of the model results
- Flooding of the seasonal flooded grasslands has been found to be directly related to the flows entering the swamps at Mongalla. It can be assumed that the relation is highly dependent on the long-term flow regime and is altered through vegetation dynamics, a matter that would need assessment in further detail

It needs to be considered that the model has been calibrated for, and delivers good results for the Bor-Mabior area, while further refinements and calibration would be necessary for areas further upstream and downstream. The results of this study will be important for future assessments including sediment and nutrient transport towards the floodplains and further assessments of infrastructural plans including dike construction projects and potential water withdrawal schemes which, depending on the amount of water diverted may have a significant impact.

Acknowledgements

The modelling platform for this study was provided by Dr. Ole Larsen, DHI Germany and proved to be a useful assessment tool under these extreme conditions. John Sutcliffe's valuable comments on a first draft are acknowledged.

Chapter VII - Summary and key findings

While several studies have been carried out in the Sudd swamps early in the last century, the system was mostly inaccessible in more recent years due to civil war. Research work was limited to coarse remote sensing and historical data. While this data allowed for a good general assessment of the swamp as for example conducted by Mohamed (2005), hydrological details and hydrodynamic processes of the central and lower sections of the Sudd north of Bor were unknown. The upper section of the Sudd between Mongalla and Bor had been studied in detail by Sutcliffe (1957). The results of this dissertation provide a detailed assessment of the Sudd area downstream of Bor, focusing on the central swamp between Bor and Shambe based on the available historical and remote sensing data as well as new measurements captured during 2004 to 2006 measuring campaigns. With the general characteristics for the central and downstream sections being similar, results may be seen valid for the whole of the Sudd downstream of Bor. Data collection downstream of Shambe was anyhow not possible within the scope of this dissertation due to accessibility reasons within the vast and remote system.

The chapters of the dissertation, submitted as individual papers in peer-reviewed scientific journals, cover a range of specific topics which are important for a full understanding of the system. These include:

- Morphological analysis of the Sudd region using land survey and remote sensing data
- Spatio-temporal water body and vegetation changes in the Nile swamps of southern Sudan
- Water balances of the Vertisol floodplains of southern Sudan
- Estimating of ungauged Bahr el Jebel flows based on upstream water levels and large scale spatial rainfall data
- Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan

In combination, these papers provide a comprehensive analysis and description of the hydrology and hydrodynamics of the swamp system downstream of Bor. Key findings include:

- The morphology of the area with its very even plains and very small gradients of 0.1 m/km provide the base for widespread flooding on the seasonal floodplains
- The water levels in the permanent swamp are directly controlled by the inflow of combined Equatorial Lakes discharges and torrent flows between the Lakes and Mongalla
- Missing Mongalla discharge measurements were successfully generated by a methodology to estimate this missing information based on upstream gauges and spatial rainfall data

- Within the permanent swamps, vegetation dynamics caused by changes in current velocities and water levels play an important role in altering the flow discharges and water levels in different parts of the swamp
- The conditions within the permanent swamp control the water balances on the seasonal floodplains
- Water balances on the seasonal floodplains are influenced by soil water recharge, soil evaporation, evapotranspiration and flow resistance due to dense grasses. The values for these parameters have been established.
- The Sudd system can be successfully modelled using a two-dimensional numerical model
- Hydrodynamic conditions in the swamps and on the seasonal floodplains during rise and fall of the flood waters have been generated, showing flow directions, velocities and water depth for typical flow events
- Being an inland delta with unrestricted floodplains north of Bor, waters spilled from the main channels into the swamps and onto the floodplains do not return to the river but are lost by evapotranspiration
- With no alluvial banks confining the river, permanent water level gradients persist throughout all seasonal conditions sloping away normal from the main channels towards the borders of the swamp with the gradient being determined by flow resistance and evapotranspiration

Chapter VIII - Discussion and conclusions

8.1 The Sudd swamp system

The assessments carried out in this dissertation have generated an overall and detailed understanding of the hydrology and hydrodynamics of the central Sudd swamps with its unlimited floodplains. The work supplements earlier studies of for example Sutcliffe (1957) who conducted detailed studies in the upper swamp section between Mongalla and Bor where the swamp is constrained in an incised trough, resulting in a different behaviour of the system. A 3D view of the area based on SRTM elevations (NASA, 2006a) overlaid with a 2002 Landsat image (NASA, 2006b) is shown in Figure 8.1. While different possible explanations regarding the swamp behaviour were suggested by Butcher (1938), evidence of the origin, behaviour and fate of the flows in the central swamps and on the floodplains has been provided in this dissertation. Results show the unidirectional flow of the spill leaving the main channels along a constant water level gradient declining from the channels towards the floodplains with the slope being shaped by flow restriction through reeds and evapotranspiration processes.

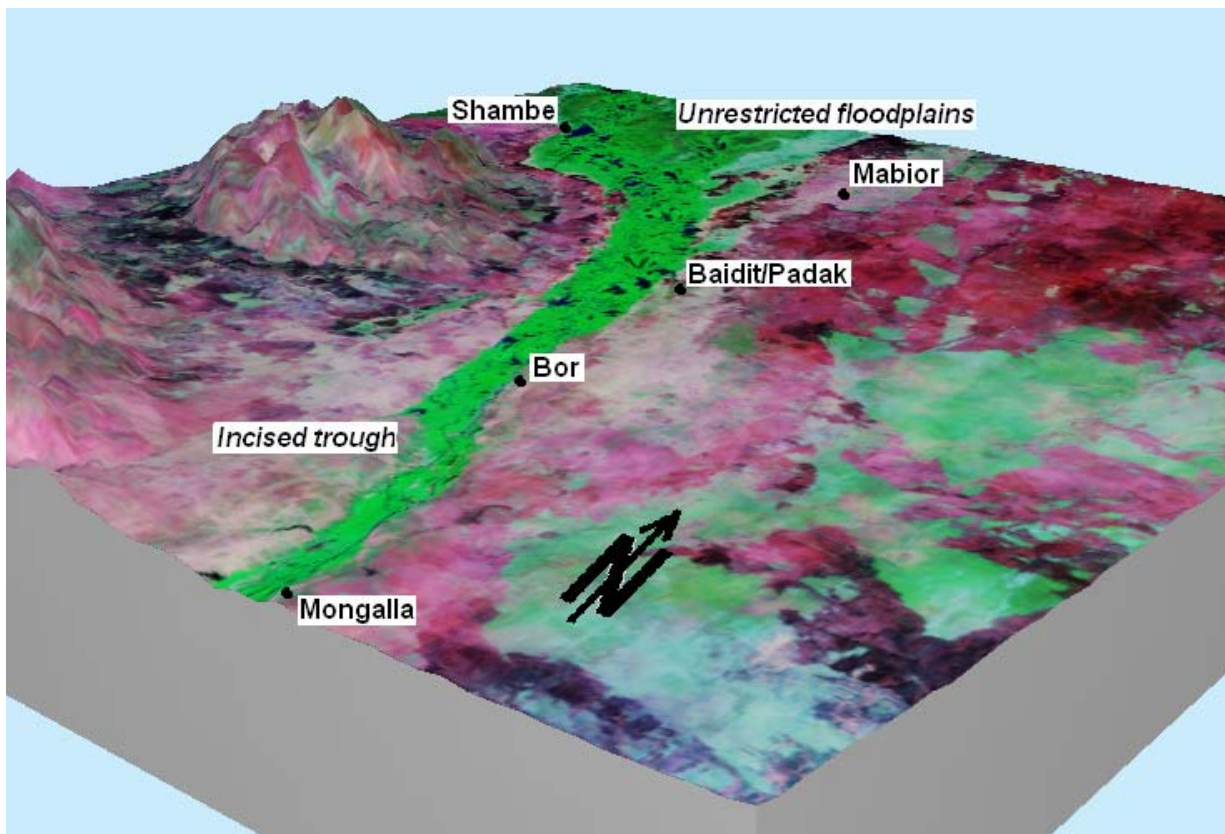


Figure 8.1: 3D view of the assessment area between Mongalla and Shambe showing the transition from incised trough between Mongalla and Bor to unrestricted Floodplains north of Bor. The elevations are exaggerated for better visualization

In contrast to earlier studies it is shown in Chapter 2 that north of Bor the river flows on an elevated ridge made up from deposits, laterally not restricted by banks but by permanently inundated vegetation, mostly papyrus and reeds. The water levels within this vegetation and the amount of permanent lateral spill are controlled by the inflow into the system at Mongalla as well as by the resistance to flow and evapotranspiration within the vegetation. On the floodplains, evapotranspiration, resistance to flow through vegetation and soil water recharge which may have been induced to a certain extent by precipitation, influence the spreading of flood waters. The central processes are shown in Figure 8.2.

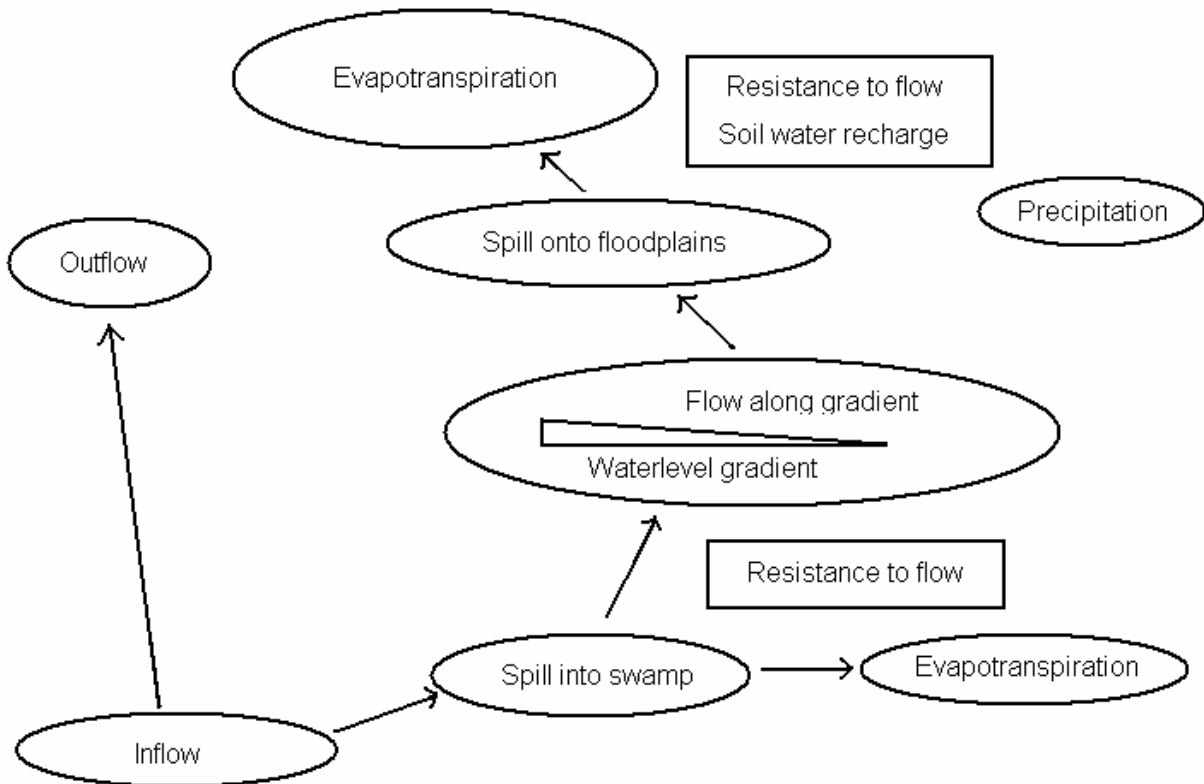


Figure 8.2: Hydrological processes in the central Sudd swamp area

Comparing the different approaches to evaluate the system using measured datasets and numerical modelling techniques, early results as shown in Chapter 2 and 4 have been confirmed and refined by the modelling approach as described in Chapter 6, clearly showing the water level gradients, flow directions and losses of waters towards the seasonal floodplains from which no return flow occurs towards the swamp. The situation is considerably different to the explanations suggested by Sutcliffe & Parks (1996) for the area between Mongalla and Bor. In the upper Sudd section where the meandering river is confined in an incised trough, waters spill from the river into a series of parallel isolated basins and return to the river at the downstream end of these basins. In the central Sudd section between Bor and Shambe on the other hand, the confining trough has disappeared and flood waters are spilled into an unrestricted floodplain. The transition is visible from DEM data as well as when comparing cross sections as shown in Chapter 2.

Another historical assumption challenged in this dissertation is the suggestion of overland flows caused by precipitation contributing runoff to the swamps (JIT, 1954). Assessments carried out in this dissertation clearly show that precipitation has a negligible influence on area flooding and that soil water recharge rates can only be exceeded in extreme rainfall events. While local area flooding through extreme rainfall events is therefore possible for short periods of time, this phenomenon would be locally restricted and not contribute runoff to the permanent swamp.

Looking at individual parameters, historical estimates have partly been confirmed and improved. Sutcliffe & Parks (1999) suggested annual evapotranspiration rates of 2150 mm, the figure being confirmed by experiments showing values of 2075 mm (Chapter 4). Soil water recharge values on the other hand were suggested as 200 mm while evaluations of experiments in Chapter 4 clearly show values of nearly double the amount, suggesting that even higher recharge values could be considered as the effect of soil cracks had not been taken into account in former studies. An assessment of the distribution of conveyance of waters has been conducted in Chapter 2, showing the 8% contribution of the vegetated swamp cross section compared to 92% of the flows conveyed in the main channels. Earlier studies (Butcher, 1938) had neglected flows within the vegetated areas only considering channel flows. Another postulation by Butcher (1938) suggested the occurrence of spill from the Bahr el Jebel towards the Bahr el Ghazal which was meant to explain the high water losses in the system which could not be explained considering the too low evapotranspiration estimates at that time. While SRTM analysis shows that no divide exists between the two basins, flow into the Bahr el Ghazal system is unlikely as waters will have evaporated before reaching there considering the low flow velocities and high evapotranspiration rates.

Chapter 5 shows the behavior of the Lake Albert outflow rating curve in response to varying Equatorial Lakes discharges, highlighting the impact of the doubled Lake Victoria outflow in 1963, caused by increased rainfall in the lake catchment. As a result, vegetation dynamics influenced by the increased outflow, caused changed flow characteristics. While in this case the rating curves were established to assess Bahr el Jebel flows at Mongalla, it is important to consider the influence of vegetation dynamics also in the Sudd swamps. While no satellite images have been available for a direct assessment, the effects need to be considered when reading Chapter 3. While the post 1963 trend with slowly decreasing inflows into the Sudd swamps causing increasing vegetation density and shrinking lagoon sizes is shown, the opposite effect of largely increased inflow conditions could not be assessed due to a lack of satellite images for this period. It can anyhow be assumed that the effects on vegetation dynamics would lead to significant changes in the system with rating curves changing similarly to those shown for Lake Albert in Chapter 5. The effect of vegetation dynamics caused by the 1963 increase in discharge can be estimated when comparing JIT (1953) maps of the channel network of the area with the post 1963 channel network maps derived from satellite images. Significant non-linear differences are visible between the pre- and post event maps, a qualitative comparison is shown in Figure 8.3.

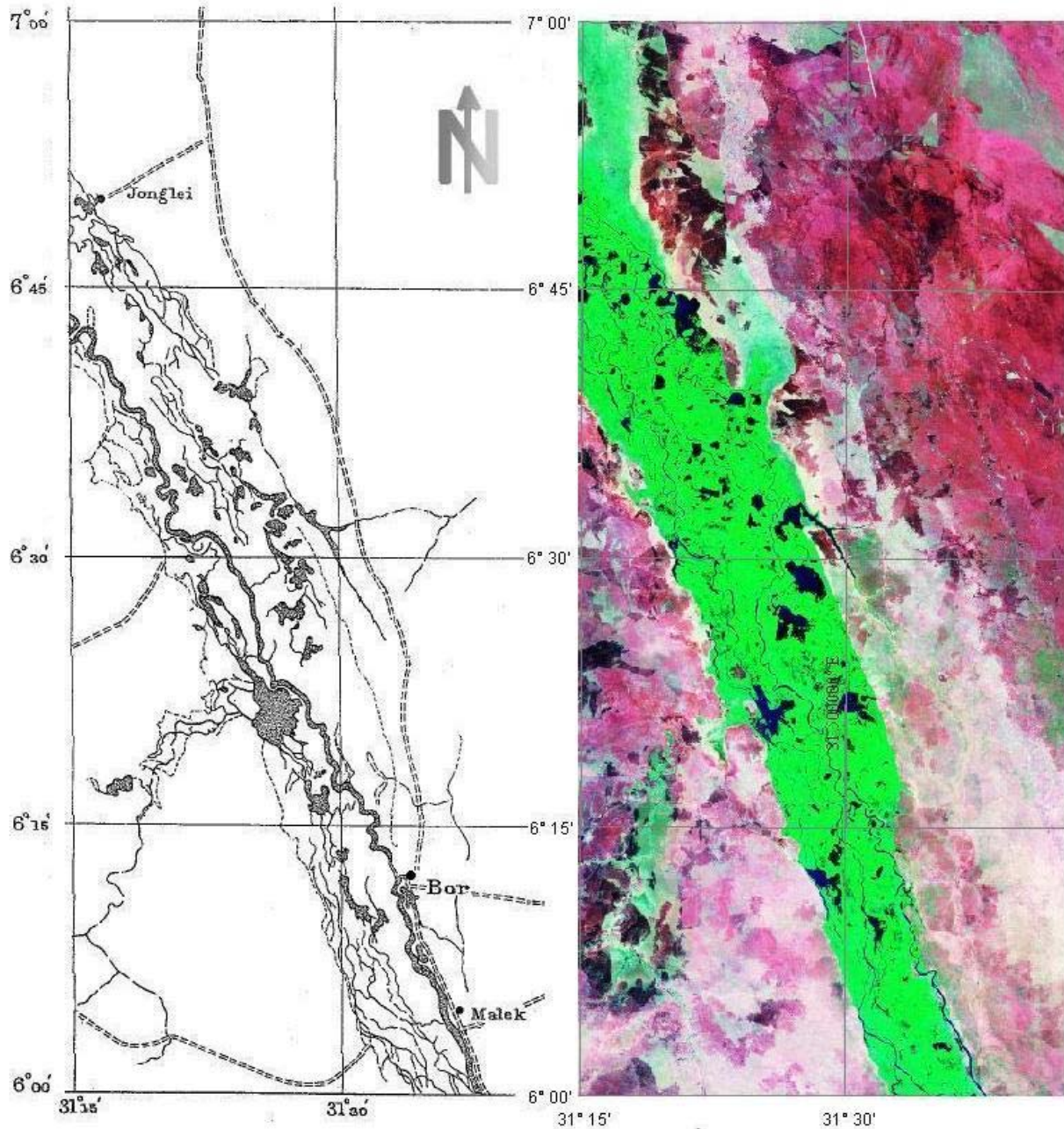


Figure 8.3: Qualitative comparison between JIT (1954) map and Landsat image of 2002 (NASA, 2006b) showing changes in the channel and lagoon system

8.2 Conclusions and outlook

Hydraulic investigations and evaluation of water balances have been carried out in the Sudd swamps of southern Sudan. The studies improve and update historical interpretations and describe so far unknown conditions and interdependences in the swamp and floodplain system, considering the area morphology, vegetation dynamics, water balances, flow conditions and hydrodynamic processes. The derived information has significantly updated the knowledge

about the predominant hydrological and hydrodynamic processes in the Sudd swamps but also highlights the need for additional studies, especially regarding the influence of vegetation dynamics which have a significant effect in altering the flow conditions in the system. While differences exist between the assessed Sudd section and the upper swamps south of Bor as discussed in Section 8.1, it can be assumed that findings and processes are generally applicable for the total swamp area downstream of Bor, where similar unrestricted floodplain conditions exist. Slopes in the downstream area are even gentler and the permanent swamp area is wider, which may lead to a slightly different flow distribution as discussed in Chapter 2. Conditions in the Bahr el Ghazal Swamps can be judged similar as well while due to differences between SRTM and ground survey data as shown in Chapter 2 further assessments based on remote sensing data are not possible without utilizing a suitable grid of ground control points for correction of the satellite data. Making this survey data available and carrying out the ground correction of the remote sensing data would be an important step in improving the base data available for the Bahr el Ghazal area. The same ground control point assessments could be used to confirm the assumptions regarding SRTM conformity made for the northern Sudd area.

Other areas where the obtained knowledge could be improved through complex assessments would include further large scale experiments of soil water recharge to include the effects of soil cracks and establish more accurate recharge values. Secondly an assessment of the processes controlling vegetation dynamics as well as the effects of vegetation changes on the river hydraulics would be of importance for a better understanding of the system. As the factors are interactive, detailed and long term assessments would be needed to understand these as well as possible related factors of importance that could impact on the vegetation.

With peace returned to southern Sudan and a huge demand for development in the region, the current results will, as they stand, provide the base for any further planning approach for infrastructural development, irrigation projects, flood security aspects and general socioeconomic considerations for the largely flood-cycle dependent pastoralist cattle grazing communities. The study will contribute to assess the upcoming questions regarding the fate of the unfinished Jonglei Canal and will help to assess the impacts of currently planned changes to the Lake Victoria outflow controls.

Bibliography

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop evapotranspiration – Guidelines for computing crop water requirements*. FAO irrigation and drainage paper 56. Rome. Italy

Baecher G. 2000. *The Nile Basin – Environmental transboundary opportunities and constraint analysis*. USAID PCE-I-00-96-00002-00

Butcher AD. 1938. *The Sadd Hydraulics*. Government Press. Cairo. Egypt

DHI. 2008. *MIKE21*. <http://www.dhigroup.com/Software/Marine/MIKE21.aspx>. Accessed 11. March 2008

DIN 11277. 1994. *Soil quality - Determination of particle size distribution in mineral soil material - Method by sieving and sedimentation*. Germany

DIN 18130. 1998. *Soil - investigation and testing; Determination of the coefficient of water permeability - Part 1: Laboratory tests*. Germany

Entenman, D.: *Geospatial Stream Flow Model (GeoSFM) Users Manual, VI.0*, FEWSNET Intern, USGS Center for EROS, Sioux Falls, SD, USA, 2006

ESRI: ArcGIS: *The Complete Enterprise GIS*, <http://www.esri.com/software/arcgis/>, 2007, Accessed 24.12.2007

Euroconsult. 1981. *Kongor Flood Protection Surveys. Draft Final Report*. Arnhem, Netherlands

Funk, C., Michaelsen, J., Verdin, J., Artan, G., Husak, G., Senay, G., Gadain, H., Magadazire, T.: *The Collaborative Historical African Rainfall Model: Description and Evaluation*. Int. J. Climatol. **23**: 47-66, 2003

Georgakakos AP, Kohm W. 1995. *A decision support system for the Nile river*. Georgia Institute of Technology, Atlanta, USA

Hassan R, Scholes RJ, Marneweck G, Petersen G, Mungatanga E, Wahungu G, Batchelor A, Thompson M, Rountree M, Lo-Liyong C, Crosskey S, Ipoto L, Kuot P, Echessah P. 2006. *Environmental Impact Assessment of the Bor Counties Dyke Rehabilitation Project*. CEEPA. Univ. of Pretoria. Pretoria

- Hofton M, Dabuyah R, Blair JB, Rabine D. 2006. *Validation of SRTM elevations over vegetated and non-vegetated terrain using medium footprint LiDAR*. Photogrammic Engineering & Remote Sensing Vol. 72, No. 3, pp. 279-285
- Howell P, Lock M, Cobb S. 1988. *The Jonglei Canal: Impact and Opportunity*. Cambridge University Press. Cambridge
- Hurst HE, Phillips P. 1931. *The Nile Basin Volume I, General Description of the Basin, Meteorology, Topography of the White Nile Basin*. Schindlers Press. Cairo. Egypt
- Hurst HE. 1932 and Supplements. *The Nile Basin, Volume II and Supplements 1-13, Measured Discharges of the Nile and its Tributaries*. Cairo. Egypt
- Hurst HE. 1933 and Supplements. *The Nile Basin, Volume IV and Supplements 1-13, Ten Day Mean and Monthly Mean Discharges of the Nile and its Tributaries*. Government Press. Cairo. Egypt
- Hurst HE, Phillips P. 1938. *The Nile Basin Volume V, The Hydrology of the Lake Plateau and the Bahr el Jebel*. Schindlers Press. Cairo. Egypt
- Hurst HE, Black P. 1943 and Supplements. *The Nile Basin Volume VI, Monthly and Annual Rainfall Totals and the Number of Rainy Days at Stations in and near the Nile Basin*. Schindlers Press. Cairo. Egypt
- IUSS Working Group WRB. 2006. *World reference base for soil resources 2006*. World Soil Resources Report No. 103. FAO. Rome
- JIT – Jonglei Investigation Team. 1954. *The Equatorial Nile Project and its Effects on the Anglo-Egyptian Sudan*. Volumes I-IV. Sudan Government. Khartoum. Sudan
- Koponen J, Kummu M. 2004. *Support to the Management of Sudd Blockage on Lake Kyoga*. ILM-EIAC. Finland
- Mefit-Babtie Srl. 1983. *Development Studies of the Jonglei Canal Area, Range Ecology Survey, Final Report, Volume 2, Background*. Khartoum. Sudan
- Migahid AM. 1948. *Report on a botanical excursion to the Sudd region*. Fouad I University Press. Cairo. Egypt
- Migahid AM. 1952. *Further observations on the flow and loss of water in the “Sudd” swamps of the upper Nile*. Fouad I University Press. Cairo. Egypt
- Mohamed YA, Bastiaanssen WGM, Savenije HHG. 2004. *Spatial Variability of Evaporation and Moisture Storage in the Swamps of the Upper Nile studied by Remote Sensing Techniques*. Journal of Hydrology **289**: 145-164

Mohamed YA. 2005. *The Nile Hydroclimatology: Impact of the Sudd Wetland*. Delft University of Technology. Delft

NASA. 2004. *ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)*. <http://asterweb.jpl.nasa.gov/>. Accessed 18. October 2006

NASA. 2006a. *Shuttle Radar Topography Mission*. <http://www2.jpl.nasa.gov/srtm/>. Accessed 11. March 2008

NASA. 2006b. *The Landsat Program*. <http://geo.arc.nasa.gov/sge/landsat/landsat.html>. Accessed 11. March 2008

NASA. 2007. *The Landsat Program*. <http://landsat.gsfc.nasa.gov>

Penman HL. 1948. Natural evaporation from open water, bare soil and grasses. *Proc. Roy. Soc.* 193, 120-145

Petersen G. 2006. *Hydrological Impacts Assessment Study for Environmental Impacts Assessment of the Bor-Mabior Dike Rehabilitation Project*. USAID. Nairobi. Kenya

Petersen G, Abya JA, Fohrer N. 2007a. *Spatio-temporal water body and vegetation changes in the Nile swamps of southern Sudan*. *Adv. Geosci.* 11, 113-116

Petersen G, Sutcliffe JV, Fohrer N. 2007b. *Morphological analysis of the Sudd region using land survey and remote sensing data*. *Earth Surf. Process. Landforms* 33

Petersen G, Bast H, Fohrer N. 2008. *Estimation of ungauged Bahr el Jebel flows based on upstream water levels and large scale spatial rainfall data*. *Adv. Geosci.* Accepted for publication.

Petersen G, Fohrer N. 2008. *Water balances of the Vertisol floodplains of southern Sudan*. *Hydrol. Sci. J.* Submitted.

Petersen G, Fohrer N. 2008. *Two-dimensional numerical assessment of the hydrodynamics of the Nile swamps in southern Sudan*. *Hydrol. Sci. J.* Submitted

PJTC. 1977. *Jonglei Structures Phase I, Hydrological Background Information for the Design of the Structures*. Euroconsult Interim Report No 2

Rodriguez E, Morris CS, Belz JE, Chapin EC, Martin JM, Daffer W, Hensley S. 2005. *An Assessment of the SRTM Topographic Products*, Technical Report JPL D-31639. Jet Propulsion Laboratory. Pasadena. California

Schoeneberger PJ, Wysocki DA, Benham EC, Broderson WD. 2002. *Field Book for Describing and Sampling Soils*. Version 2.0. NRCS-NSSC. Lincoln. USA

Sutcliffe JV. 1957. *The Hydrology of the Sudd Region of the Upper Nile*. PhD Thesis. Cambridge University. Cambridge

Sutcliffe JV. 1974. *A Hydrological Study of the Southern Sudd Region of the Upper Nile*. Hydrol. Sci. Bulletin 19, 2 6/1974: 237-255

Sutcliffe JV, Parks YP. 1987. *Hydrological modelling of the Sudd and Jonglei Canal*. Hydrol. Sci. J. **32**, 2, 6/1987

Sutcliffe JV, Parks YP. 1996. *Hydrological controls of Sudd Ecology*. In: Water Management and Wetlands in Sub-Saharan Africa. Edited by Acreman AC, Hollis GE. 51-72. IUCN. Gland. Switzerland

Sutcliffe JV, Parks YP. 1999. *The Hydrology of the Nile*. IAHS Special Publication No 5. Wallingford. UK

Trimble Ltd. 2007. *Differential GPS*. <http://www.trimble.com/gps/dgps.shtml>. Accessed 17. May 2007

Wallingford Software Ltd. 2006. *Conveyance Estimation System*. Wallingford, UK

World Bank - UNDP. 1989. *Sub Saharan Hydrological Assessment, Final Report, Sudan*. RAF/87/030. Alexander Gibb & Partners, Reading, UK

World Bank. 2008. *Nile Basin Initiative Overview*. <http://go.worldbank.org/1J4ISEE170>. Accessed 22.March 2008

List of Figures

Figure 1.1: The Nile in southern Sudan with the core area of interest between Mongalla and Shambe (modified from World Bank, 2008)

Figure 1.2: Permanent swamp with active main channel, lagoons and papyrus area

Figure 1.3: 2002 Landsat (NASA, 2006b) image of the Sudd area of southern Sudan in its full extent between the main historical gauging stations of Mongalla in the south and Malakal in the north. Most studies in this dissertation have been carried out between Bor and Shambe

Figure 1.4: Inflow at Mongalla, outflow at Malakal and losses in the Sudd area derived from Hurst (1932 and Supplements). High losses, damping and delay of peaks are visible when comparing Mongalla inflows with outflows at Malakal of which River Sobat inflows at Doleib have been deducted.

Figure 1.5: Papyrus, reeds and water hyacinth in the main swamp area near Baidit/Padak in April 2004

Figure 2.1: Overview of project area in southern Sudan with detailed core area of interest

Figure 2.2: Layout of Khor Baidit and Adwar

Figure 2.3: Water level (WL) time series of Burakok (within the Swamp) and at the tails of Khor Adwar and Khor Baidit showing surface level fluctuations in correlation to the wet and dry season. (Note that the station at Khor Adwar is not cut off but located just to the west of the road dam)

Figure 2.4: Depth profile along Bahr el Jebel main channel from south to north between Bor and Shambe. In the upstream part the depths are variable, but less so further downstream after chainage 30 km. The trend line shows an interpolated moving average of the depth

Figure 2.5: SRTM DEM of the area between Bor and Shambe showing an inland delta formation. The transition from incised trough in the south to elevated channels in the north is clearly visible

Figure 2.6: Comparison of SRTM DEM and land survey elevation. The depression in the DEM data is clearly visible both on the map (light area) as well as in the graph, representing levels along the course of the Bahr el Ghazal from upstream Meshra el Rek (1) to Lake No (5). The land survey elevations for the stations Meshra el Rek, Ghabat el Arab, Yoynyang (near Bentiu) and Lake No are deduced from data collected by Hurst (1933), corrected to NKL + 6.8 m and show the discrepancy from the DEM data

Figure 2.7: Series of cross sections between Mongalla and Buffalo Cape near Lake No extracted from SRTM DEM. The sections are taken looking downstream showing the transition from incised trough to elevated deltaic formation as well as the slope towards the Bahr el Ghazal basin in the northern (lower) areas

Figure 2.8: Comparison of JIT (1954) and SRTM derived cross sections 2 km upstream of Terakeka

Figure 3.1: Aerial photograph of the permanent swamp area with channels, lagoons, floating and anchored vegetation areas, taken during an aerial assessment in 2004 over the swamps near Baidit/Padak

Figure 3.2: Area overview map derived from Landsat image interpretation

Figure 3.3: Overlaid channel system of the years 1973, 1979, 1997 and 2002 of the area of Maar – Jonglei, indicatively showing the general trends of channel movements and decrease in channel width

Figure 3.4: Overlaid lagoon system of the years 1973, 1979, 1997 and 2002 of the Padak - Jalle area indicating the decrease in lagoon area

Figure 3.5: Lake Victoria outflow at Jinja (after data from Hurst, 1933 and supplements) with marked years of evaluated satellite data

Figure 4.1: Overview of the Sudd swamps between Bor and Shambe. The image shows main channels and lagoon areas.

Figure 4.2: Geological cross section generated from drilling profiles of the Bor – Shambe area from OLS Water, Kenya

Figure 4.3: Grain size distribution of averaged surface (< 1 m depth) and subsurface (> 1 m depth) soil layers

Figure 4.4: Soil water recharge and rainfall between January 2005 and April 2006

Figure 4.5: Soil evaporation values during an average daily cycle

Figure 4.6: Evapotranspiration from the October/November 2005 depression experiment showing daily evaporation rates as well as correlation between rainfall events and water level fluctuations

Figure 4.7: Comparison of calculated and measured daily evapotranspiration values

Figure 4.8: Observed conditions in the seasonal flooded grassland areas

Figure 4.9: Water level fluctuations at different locations in the seasonal flooded grassland area compared to levels at Burakok station within the permanent swamps

Figure 4.10: Soil water recharge in October and November 2005 based on rainfall data combined with measured and calculated evapotranspiration values. The point of soil saturation of 350 mm is not reached. Rain received before October has at this point already evaporated. The discrepancy between the two curves can be explained by measurement problems

Figure 4.11: Indicative water budget of the seasonal flooded grasslands (riverfed) during an annual flooding cycle

Figure 5.1: Area overview prepared from Landsat satellite imagery showing Lake Albert, the torrent catchment area and Mongalla gauging station. The Sudd swamps are located north of Mongalla, Lake Victoria is south of Lake Albert

Figure 5.2: Catchment area at Nimule. Looking west, Nimule is in the centre of the image and the distinctive right angle Nile bend is visible on the left

Figure 5.3: Principles of data processing and interactions utilizing timeseries (1-3) and spatial rainfall data (4-7) which are then combined (8-9) to calculate Mongalla flows.

Figure 5.4: Dry season rating curves for Lake Albert outflow for periods with different typical flow conditions based on Lake Victoria outflow

Figure 5.5: Comparison of calculated and measured Lake Albert outflow based on the relevant rating curve and calibrated using a correction coefficient, gaps are caused by missing input data

Figure 5.6: Comparison of calculated and measured Mongalla flows 1961 to 1983 as well as estimated Mongalla flows 1984 to 1996, gaps are caused by missing data, the baseflow from 1984 to 1996 is interpolated due to few available measurements

Figure 6.1: Overview of the assessment area; the model was set up between Mongalla and Shambe, the image shows main channels and lagoons in this area. The core area of interest, which has been assessed in detail, is located on the right bank between Baidit/Padak and Jalle

Figure 6.2: Papyrus - dense swamp vegetation with a height of typically between 3 and 5 m

Figure 6.3: Schematic cross section of the Sudd swamps north of Bor

Figure 6.4: Flows at Mongalla and water level records, corrected to SRTM levels, at different locations in the southern Sudd swamps derived from Hurst & Phillips (1932 and Supplements). Flows and levels are directly related as shown in the inlay. The locations of the numbered stations are shown in Figure 6.5

Figure 6.5: Dry season Landsat image of the model area showing the swamp with monitoring station numbers and locations as well as the enlarged core assessment area between Baidit/Padak and Jalle.

Figure 6.6: Water depth, inundation extent and velocities under typical dry season low flow conditions ($1000 \text{ m}^3/\text{s}$ swamp inflow at Mongalla). While the channel flow velocities are well visible, flow velocities within the papyrus areas are hardly visible due to their small values

Figure 6.7: Water depth, inundation extent and velocities under typical rainy season high flows ($2000 \text{ m}^3/\text{s}$ swamp inflow at Mongalla) in the core assessment area. Water is flowing down the seasonal floodplains which are inundated under these conditions

Figure 6.8: Inflow-level relation for different station locations in the model area as shown in Figure 6.5. The curves may vary depending on the long-term flow regime with related vegetation dynamics. Station names are given together with the respective station numbers

Figure 6.9: Modeled and measured water level gradient along a line from the center of the swamps through lagoons and khors onto the seasonal flooded grasslands under rainy season average high flow conditions ($2000 \text{ m}^3/\text{d}$ at Mongalla). The Landsat background image shows dry season conditions for better visualization

Figure 8.1: 3D view of the assessment area between Mongalla and Shambe showing the transition from incised trough between Mongalla and Bor to unrestricted Floodplains north of Bor. The elevations are exaggerated for better visualization

Figure 8.2: Hydrological processes in the central Sudd swamp area

Figure 8.3: Qualitative comparison between JIT (1954) map and Landsat image of 2002 (NASA, 2006b) showing changes in the channel and lagoon system

List of Tables

Table 1.1: Main vegetation species found in the Sudd area

Table 2.1: Levels used for comparison of Euroconsult NKL values; DGPS measurements and SRTM DEM extracted levels from which correction factors were deduced in the area between Baidit/Padak and Mabior. Locations are given as road and dike chainages from Baidit/Padak to the north

Table 2.2: Percentage distribution of swamp type over different cross sections

Table 2.3: Cross sectional flow analysis averaged over the different measured cross sections between Bor and Shambe

Table 3.1: Main species inhabiting the Sudd swamps after data from JIT (1954)

Table 4.1: Parameters and values used for average evapotranspiration calculations after FAO Penman-Monteith for the October/November 2005 period

Table 4.2: Meteorological data for the Bor – Shambe area. Monthly averages for April 2005 to August 2006

Table 4.3: Evapotranspiration values calculated after FAO Penman-Monteith for the Bor – Shambe region

Table 5.1: Availability of data for different locations

Table 5.2: Regression functions for dry season Lake Albert outflow for different periods as shown in Figure 5.4

Table 5.3: Statistical characteristics of Lake Albert outflow ($10^6 \text{ m}^3/\text{month}$) (mean, minimum, maximum, standard deviation, and correlation coefficient between measured and calculated values). The outflow was calculated from lake level readings with regression functions of Table 5.2 for the calibration periods f and h with available measured flow data at Panyango.

Table 5.4: Statistical characteristics of Mongalla flows ($10^6 \text{ m}^3/\text{month}$) (mean, minimum, maximum, standard deviation, and correlation coefficient between measured and calculated values)

Table 6.1: Sensitivity parameters

