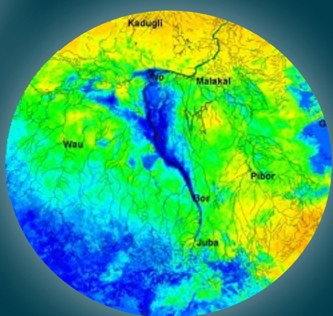
2010

GIS Based Decision Support Tool for Sustainable Development of SUDD Marshes Region (SUDAN)



Nile Basin Capacity Building Network

NBCBN-RE

2010

GIS Based Decision Support Tool for Sustainable Development of SUDD Marshes Region (SUDAN)

"Key knowledge"

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NBCBN - BACKGROUND

Project Title
Knowledge Networks for the Nile Basin
Using the innovative potential of Knowledge Networks and CoP's in strengthening human and institutional research capacity in the Nile region.
Implementing Leading Institute
UNESCO-IHE Institute for Water Education, Delft, The Netherlands (UNESCO-IHE)
Partner Institutes
Ten selected Universities and Ministries of Water Resources from Nile Basin Countries.
Project Secretariat Office
Hydraulics Research Institute – Cairo - Egypt
Beneficiaries
Water Sector Professionals and Institutions in the Nile Basin Countries

Short Description

The idea of establishing a Knowledge Network in the Nile region emerged after encouraging experiences with the first Regional Training Centre on River Engineering in Cairo since 1996. In January 2002 more than 50 representatives from all ten Nile basin countries signed the Cairo Declaration at the end of a kick-off workshop was held in Cairo. This declaration in which the main principles of the network were laid down marked the official start of the Nile Basin Capacity Building Network in River Engineering (NBCBN-RE) as an open network of national and regional capacity building institutions and professional sector organizations.

NBCBN is represented in the Nile basin countries through its nine nodes existing in Egypt, Sudan, Ethiopia, Tanzania, Uganda, Kenya, Rwanda, Burundi and D. R. Congo. The network includes six research clusters working on different research themes namely: Hydropower, Environmental Aspects, GIS and Modelling, River Morphology, flood Management, and River structures.

The remarkable contribution and impact of the network on both local and regional levels in the basin countries created the opportunity for the network to continue its mission for a second phase. The second phase was launched in Cairo in 2007 under the initiative of; Knowledge Networks for the Nile Basin. New capacity building activities including knowledge sharing and dissemination tools specialised training courses and new collaborative research activities were initiated. The different new research modalities adopted by the network in its second phase include; (i) regional cluster research, (ii) integrated research, (iii) local action research and (iv) Multidisciplinary research.

By involving professionals, knowledge institutes and sector organisations from all Nile Basin countries, the network succeeded to create a solid passage from potential conflict to co-operation potential and confidence building between riparian states. More than 500 water professionals representing different disciplines of the water sector and coming from various governmental and private sector institutions selected to join NBCBN to enhance and build their capacities in order to be linked to the available career opportunities. In the last ten years the network succeeded to have both regional and international recognition, and to be the most successful and sustainable capacity building provider in the Nile Basin.

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FOREWORD

This report is one of the final outputs of the research activities under the second phase of the Nile Basin Capacity Building Network (NBCBN). The network was established with a main objective to build and strengthen the capacities of the Nile basin water professionals in the field of River Engineering. The first phase was officially launched in 2002. After this launch the network has become one of the most active groupings in generating and disseminating water related knowledge within the Nile region. At the moment it involves more than 500 water professionals who have teamed up in nine national networks (In-country network nodes) under the theme of "Knowledge Networks for the Nile Basin". The main platform for capacity building adopted by NBCBN is "Collaborative Research" on both regional and local levels. The main aim of collaborative research is to strengthen the individual research capabilities of water professionals through collaboration at cluster/group level on a well-defined specialized research theme within the field of River and Hydraulic Engineering.

This research project was developed under the "Cluster Research Modality". This research modality is activated through implementation of research proposals and topics under the NBCBN research clusters: Hydropower Development, Environmental Aspects of River Engineering, GIS and Modelling Applications in River Engineering, River Morphology, flood Management, and River structures.

This report is considered a joint achievement through collaboration and sincere commitment of all the research teams involved with participation of water professionals from all the Nile Basin countries, the Research Coordinators and the Scientific Advisors. Consequently the NBCBN Network Secretariat and Management Team would like to thank all members who contributed to the implementation of these research projects and the development of these valuable outputs.

Special thanks are due to UNESCO-IHE Project Team and NBCBN-Secretariat office staff for their contribution and effort done in the follow up and development of the different research projects activities.

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Resources are key factors in human survival and progress. Therefore, carful management and wise use is needed to preserve human needs and ecosystem. Through the different phases of the Nile Basin Capacity Building Network (NBCBN) for river Engineering scientists, engineers and specialist have been working closely to conduct many research activities to protect and develop the available water resources.

This report is an attempt to offer access to what has been done from research activity related to Sudd Marshes region in southern Sudan.

The research team would like to express their appreciation to those who have made this publication a reality, especially the management team of the NBCBN, and the research technical advisors.

EXECUTIVE SUMMARY

This research activity is one of research outputs conducted under the NBCBN. The main goal is to explore the potential aspects to be developed in the Sudd Marshes region in southern Sudan. The Sudd is a vast swamp in the lower of Bahr el Jebel (White Nile). Sudd was designated as a Ramsar site in 2006. The wise use of wetlands according to Ramsar Convention is the sustainable utilization of the wetlands for the benefit of mankind in a way compatible with the maintenance of the natural properties. The objectives are to improve livelihood of the local people, reducing poverty, and conserving the ecosystem services. However, the achievement of these objectives needs an accurate knowledge of the water balance components over the wetland as well as the potential socioeconomic and environmental aspects. This research is an initiative attempt to explore the potential entities can be used as a key knowledge for Sudd Marshes wetland development.

From the available natural resources, it can be concluded that the ecology of the Sudd wetland is composed of various ecosystems, grading from open water and submerged vegetation, to floating fringe vegetation, seasonally inundated woodland, rain-fed and river-fed grasslands, and floodplain scrubland. It is a wintering ground for birds of international and regional conservation importance such as Pelecanus onocrotalus, Balearica pavonina, Ciconia ciconia and Chlidonias nigra; and is home to some endemic fish, birds, mammalian and plant species, and to the vulnerable Mongalla gazelle, African elephant and shoebill stork. Migratory mammals depend on the wetland for their dry season grazing. Hydrologically the Sudd wetland is regarded as a giant filter that controls and normalizes water quality and a giant sponge that stabilizes water flow. It is the major source of water for domestic, livestock, and wildlife use, and an important source of fish. The occupants living within and adjacent to the Sudd region are almost exclusively Dinka, Nuer and Shilluk. The socio-economic and cultural activities of these Nilotes are entirely dependent on the Sudd wetland and on its annual floods and rains to regenerate floodplain grasses to feed their cattle. They move from their permanent settlements on the highlands to dry season grazing in the intermediate lands (toich) at the beginning of the dry season and return to the highlands in May-June when the rainy season starts. Oil exploration as Sudd contains Sudan’s largest oil block has direct impact on the environment. There are potential risks of air, water, and soil pollution for plants, wildlife, birds, livestock and human being. This may result that the produced water contains toxic and cancerous chemical. Jonglei Canal Project, which is currently on hold, but would reduce wet and dry season flows by 20 and 10% respectively, thus impacting the wetland’s ecology and consequently its inhabitants. There are three protected areas within the Sudd, but no special protection measures or management plan is in place. Therefore, the following potential can be defined for management and developments:

- Human livelihood
- Land use management
- Vegetation resource management
- Livestock management (production and marketing)
- Species management
- Fisheries and aquacultures
- Flood and draught threats management
- Waste management
- Wildlife management
- Oil and water resource management
- Hunting legalization
- Tourism improvement and management
- Water resource reservation
- Settlement management
- Impact of Jonglei Canal project on water resources and ecosystem

Due to the lack of field data, a methodology for mapping the Sudd extents using satellite images with minimum field work was developed. The methodology is based on the vegetation index where the separation of vegetation, open water, and soil can be possible. Different sets of images are used to achieve the study objectives. Spot satellite NDVI product, Landsat satellite images, and SRTM digital elevation model are among the used sets. Old topographic maps of the area are used as a ground truth dataset to verify the images. The study results include maps of monthly average Sudd region extents, monthly surface area of open water and vegetation, and land cover classification maps. The minimum and maximum buffers that surrounding the extents of the Sudd area were estimated for both dry and wet seasons as 17,000 and 45,632 km^2 respectively. The study recommends that using additional sources of aqua-satellite images to define the actual extent of the permanent and seasonal wetland to minimize the error from vegetation mixed with water.

Hydrological and hydraulic modeling of the Sudd are key to the understanding of the behavior of the wetland and its role in shaping the ecology and the economy of the region. This has always been hindered by the difficulty to monitor water levels and areal extents of this vast area from the ground. Satellite remote sensing provides opportunities to avail information about the behavior of the wetland and this study attempts to utilize such information to calibrate a hydrolological model of the wetland as an important component in building knowledge about the area. The main objective of such model is to predict the swamp area and the Sudd outflow to help evaluate the impacts of climate and land use changes over the area. The study used satellite-based estimates of the Sudd area over the period 1999-2006 to calibrate a simple hydrological model of the swamps. Other inputs to the model included rainfall over the swamps, evapotranspiration from swamp vegetation, inflows estimated at Mongalla from levels measured at Juba, and outflows estimated as the difference between White Nile flows at Malakal and Sobat flows at Hillet Doleib (estimated from a hydrological model). Flow datasets were generally limited and had no overlap with the obtained series of areal extents and thus records had to be completed using several methods. Rainfall over the Sudd area was found to have a minor effect on the annual amount of losses. The inflow at Mongalla was found to be the most controlling factor of the areal extents of, and therefore the losses from, the Sudd. Model performance was inadequate due to several issues that had to be addressed. These include: calibration of satellite rainfall estimates using available raingauges, ground truthing of estimated areas, and inclusion of inter-annual variability of evapotranspiration (using global datasets or satellite-based algorithms like SEBAL and METRIC), and probably revising model structure. A more complicated swamp model (including hydrodynamic features) may be needed to improve the study results. However, data limitations have to be overcome before increasing model complexity.

Sudd Marshes sustainable management required the compilation of local, national, and international participations. In addition, the initiated and existing projects and programs should be taken into consideration to identify priority areas of interventions. Some of these areas can be identified as follows:

1. Education.
2. Improving techniques.
3. Awareness and responsibility allocation among different stakeholders and various levels
4. Media engagement
5. Stakeholder analysis taken into consideration the distant stakeholders
6. Proper legislations for human and environments
7. Sustainable land use and land tenure systems
8. Water management for better management of soil and water conservation practices
9. Mechanism for mitigating disasters
10. Inventory and base map for available resources
11. Promote marketing of livestock at national and regional levels
12. Overgrazing management
13. Design livestock movement and raise awareness
14. Development of tools to influence policy makers
15. Conflict resolution mechanism through mitigation of over fishing and grazing
16. Define the tourism potential and capacity, Predict impacts, and apply safe environmental practices in tourism activities

17. Policy safeguard for protected area
18. Avoid intervention and disturbance of migration routes
19. Impact assessment for any new project or exploration
20. Apply mitigation measures in suitable time
21. Establish quick technique to assess water pollutant
22. Establish an irrigation system for efficient management
23. Health facility for human and ecosystem

Key knowledge for management tools is introduced. Two mathematical models are defined; MIKESHE and MODFLOW. The basic elements for designing Decision support system for the Sudd Marshes are also highlighted.

ABBREVIATIONS & ACRONYMS

ACT	Australian Capital Territory
ANN	Artificial Neural Network
CFC_s	ChlorFluoroCarbons
CGCM 3.1	The GCM model of the Canadian Centre for Climate Modeling & Analysis, Canada
CHARM	Collaborative Historical African Rainfall Model
CNRM-CM3	The GCM model of the Meteo-France/Centre National de Researches Meteorologique, France
CRU TS2.1	The time series data of the Climate Research Unit data, Version 2.1
CWPPRA	Coastal Wetlands Planning, Protection and Restoration Act
ENSO	El Nino Southern Oscillation
EPA	Environmental Protection Agency
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization of the United Nations
GCM_S	General Circulation Models
GFDL	Geophysical Fluid Dynamics Laboratory, USA
GIS	Geographical Information System
GtC	Gitatonnes of Carbon
HAD	High Aswan Dam
HEC-HMS	Hydrologic Modeling System (HMS) developed at the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers
IMIS	Integrated Management Information System
IPCC TAR	Third Assessment Report of the Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate change
ITC	International Institute for Goe-information Science and Earth Observation
MAP	Mean Areal Preciptation
MWRI	Ministry of Water Resources and Irrigation
NBCBN-RE	Nile Basin Capacity Building Network for River Engineering
NDVI	Normalized Difference Vegetation Index
NFC	Nile Forecast Center
NFS	Nile Forecast System
NGO	Non Governmental Organization
NIR	Near Infrared
NOAA-AVHRR	National Oceanic Atmosphere Administration Advanced Very High Resolution Radiometer
PET	Potential Evapotransipiration
SDCWA	San Diego Country Water Authority
SEBAL	Surface Energy Balance Algorithm for Land
SISM	Southern Illinios Swamp Model
SPLA	Southern Sudanese Rebels
TAR	Third Assessment Report
TM	Thematic Mapper
UNESCO	United Nation Educational, Science and Cultural Organization
USA	United States of America
USGS	United States Geological Survey
WAIS	West Antarctic Ice Sheet

Chapter 1. Introduction

1.1 Description and location

The Sudd is a vast swamp (see Figure 1.1) located in Southern Sudan in the lower of Bahr el Jebel (White Nile). The area which the swamp covers is one of the Africa's largest tropical wetlands and the largest freshwater wetland in the Nile basin. The Sudd stretches from Mongalla to just outside the Sobat confluence with the White Nile just upstream of Malakal as well as westwards along the Bahr el Ghazal. Its size is highly variable, averaging over 30,000 square kilometers. During the wet season it may extend to over 130,000 km², 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 that Sudd area, consisting of various meandering channels, lagoons, reed- and papyrus fields, loses half of the inflowing water through evapo-transpiration in the permanent and seasonal floodplains. The wetland supports a diversity of ecosystems with a rich flora and funa. The swamps consist of wide blankets of high vegetation: papyrus, reeds, elephant grass, etc., which extend from the river bed to the dry ground on either side, interrupted only by lagoons and side channels. To the west of the Sudd there are the smaller wetlands of the central Baher el Ghazal Basin, and in the east is the Machar marshes of the Sobat River. Sudd was designed as a Ramsar site in 5 June 2006, World Environment Day. In that day Sudan announced the designation of the Sudd marshes as country's second wetland of International Importance, along with the Dinder National Park Ramsar Site and UNESCO Biosphere Reserve. However, the Sudd still required an intensive assessment of its potential for wise use. The wise use of wetlands according to Ramsar Convention is the sustainable utilization of the wetlands for the benefit of humankind in a way compatible with the maintenance of the natural properties. The net objectives are to improve livelihood of the local people, reducing poverty, and conserving the ecosystem services. However, Wetland wise use and development requires an accurate knowledge of the water balance components over the wetland as well as the potential socioeconomic and environmental aspects. This research is an initiative attempt to explore the potential entities can be used as a key knowledge for Sudd marshes wetland development. This research activity is supported by the Nile Basin Capacity Building network for River Engineering. The study aims at introducing the key information and knowledge which can help in wise use of Sudd wetlands.

1.2 Problem statement

The Sudd is inhabited by the Nilotic tribes (Denka, Nuer, Shuluk), and is considered one of the harshest places to live on earth. The area has been severely devastated by long civil wars. No doubt, the Sudd people are amongst the poorest in the world, frequently hit by famines and starvation, caused primarily by social instability, but possibly also by natural shocks such as drought and floods. However, the wetland is also well endowed with rich natural resources to support the livelihoods of the people, while still maintaining the health of the ecosystems. At present, the area is attracting large number of the displaced people after the peace agreement of 2005. The Sudd Marshes is composed of permanent and seasonal swamps. The exact boundaries of the swamp are difficult to specify. Attempts to define its size are based on hydrological models [Sutcliffe and Parks, 1999], on remote sensing [Travaglia et al., 1995], or on both. The Sudd is generally very flat with clayish soils. Rainfall is around 800 to 900 mm/yr, occurring from April to November. Daytime temperature is on average 30-33°C during the dry season, dropping to an average of 26 to 28°C in the rainy season. The relative humidity exceeds 80% during the rainy season, and drops to below 50% in the dry season. The swamps and floodplains of the Sudd support a rich ecosystem, which is essential to the pastoral economy of the local inhabitants. To the west of the Sudd there are the smaller wetlands of the central Baher el Ghazal Basin, and in the east is the Machar marshes of the Sobat River.

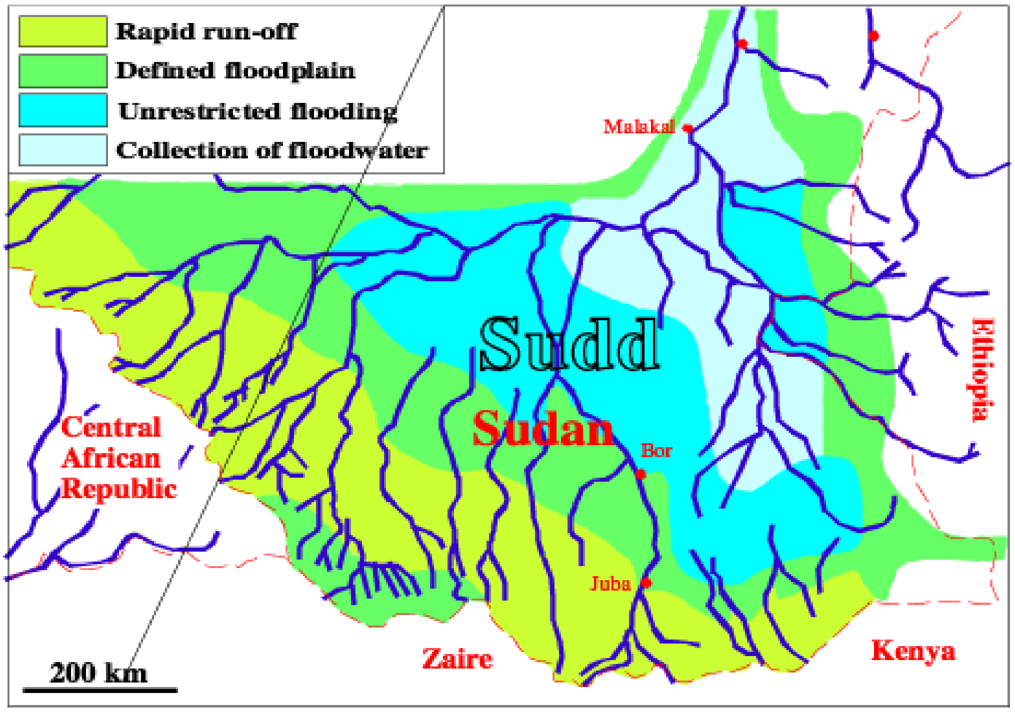


Fig.1.1: Sudd marshes location in Sudan

The Jonglei Canal project aims at reducing the heavy water losses in the Sudd Marshes region which are estimated to be about half of the river's discharges passing Mongalla. This was to be achieved through the construction of a diversion canal from Bor on Bahr El jebel to carry the water in excess of Bahr el Jebel's conveyance capacity without undue loss. Conservation of water and improvement of the ecology of the Sudd region are the twin objectives of the Jonglei Canal project. The flood regime and hydrology of Bahr el Jebel and the Sudd region in general limit any development in the area. The provision of flood control, irrigation, drainage, and transportation facilities are a sine qua non for unleashing the growth and development potential of this important region of the Sudan with multiplier effects for the Sudanese economy at large. The canal aims at providing additional water of about 5% of the Nile flow at Aswan, and it may dry 30% of the Sudd swamps [Howell et al., 1988]. However, the work on the canal stopped in 1983 due to the civil war in Southern Sudan. The signing of peace agreement between North and South Sudan is the starting point for developing the southern part of Sudan. Developing and sharing natural resources is the biggest challenge for both sides in particular water. This study will introduce the potential for integrated use of Sudd wetland resources to improve livelihood of the local people, reducing poverty, and conserving the ecosystem services. It will provide the tools and capacity for better decision making at the region taking into consideration the possible effects of climate changes as well as the human intervention.

1.3 Study objectives

The study main objectives can be summarized as follows:

1. Detect the area changes (time series analysis) by using remote sensing data
2. Formulation of simple water balance model.
3. Calibration of the simple model to predict area, outflow based on remote sensing data.
4. Introducing the potential for sustainable development options of the Sudd area.

1.4 Scope of work

- **Literature review on the following topics:**
    1. Swamp definition and Types of wetlands and their ecological functions
    2. Examples of swamps and their different functions
    3. Hydrological modeling and water quality modeling of swamps
    4. Losses in swamps
    5. Climate Changes and their effects on water resources
    6. Summary of previous studies on the Sudd region
- **Data collection on the Sudd region:**
    1. Images in different dates to represent High, medium, and low flood volume
    2. Hydrological and meteorological parameters
    3. Different resources in Sudd Area
    4. Socioeconomic data (population, income, health, education, etc)
- **Time series analysis using remote sensing data**

Water as a land cover class will be detected from the satellite image and verified using ground truthing. The water detection will be applied using vegetation index technique and the ground truthing will be obtained from supervised land cover classification of the satellite images.

- **Sudd Marshes Simulation tool (water balance model)**

This tool will include simple hydrological (water balance) model, Sutcliffe and Parks (1987). The model will be calibrated to predict area, and outflow based on remote sensing data. The tool frame has to be developed using GIS technology.

- **Introducing the available resources and assessing the potential for developments**
- **Developing different options for sustainable development of the area**

Different development option and scenarios will be recommended.

1.5 Expected outputs

1. Geo-database
2. Strengthen the knowledge on the Sudd available resources
3. Hydrological model
4. Need assessment for future sustainable development
5. Sudd Marshes simulation tool
6. Ramsar related issues to be followed in the recommended development

1.6 Using the results

Many results (outputs) will be coming out of this research. The end user of the outputs are; researchers, governmental institutions, Consultant, and NGO. The outputs will be disseminated by different methods:

1. Sudd Marshes simulation tools and time series analysis
2. Deploy all the reports and literature review on the NBCBN web site.
3. Deploy the geo-database on the NBCBN site.
4. Publish the results in international conferences whenever it is possible.

Chapter 2. Review of Literature

2.1 Introduction

The Sudd marshes in Sudan is a very famous region and it attracts many of researchers and scientists working in the field of water resources and hydrology. The sustainable development issues of wetlands require multidisciplinary team and tremendous amount of literature to be reviewed. This chapter represents a comprehensive literature review to highlight the state of the art in the fields of swamp definitions, types, hydrological modeling, climate changes, and swamp sustainable development.

2.2 Swamp

2.2.1 Definitions

A swamp is a wetland that features temporary or permanent inundation of large areas of land by shallow bodies of water, generally with a substantial number of hummocks, or dry-land protrusions, and covered by aquatic vegetation, or vegetation that tolerates periodical inundation. The water of a swamp may be fresh water or salt water. A swamp is also generally defined as having no substantial peat deposits.

Swamp could also be defined as forested wetlands. Like marshes, they are often found near rivers or lakes and have mineral soil that drains very slowly. Unlike marshes, they have trees and bushes. They may have water in them for the whole year or for only part of the year. Swamps vary in size and type. Some swamps have soil that is nutrient rich; other swamps have nutrient poor soil. Swamps are often classified by the types of trees that grow in them.

Swamps start out as lakes, ponds or other shallow bodies of water. Over time, trees and shrubs begin to fill in the land. Plants die and decay and the level of the water gets lower and lower. Eventually, the original body of water becomes a swamp.

2.2.2 Types

There are many different kinds of swamps, ranging from the forested red maple, (*Acer rubrum*), swamps of the Northeast, to the extensive bottomland hardwood forests found along the sluggish rivers of the Southeast. Swamps are characterized by saturated soils during the growing season, and standing water during certain times of the year. The highly organic soils of swamps form a thick, black, nutrient-rich environment for the growth of water-tolerant trees such as cypress (*Taxodium* spp.), Atlantic white cedar (*Chamaecyparis thyoides*), and tupelo (*Nyssa aquatica*). Some swamps are dominated by shrubs, such as buttonbush or smooth alder. Plants, birds, fish, and invertebrates such as freshwater shrimp, crayfish, and clams require the habitats provided by swamps. Many rare species, such as the endangered American crocodile depend on these ecosystems as well. Swamps may be divided into two major classes, depending on the type of vegetation present: shrub swamps, and forested swamps.

Forested swamps: are found throughout the United States (Figure 2.1). They are often inundated with floodwater from nearby rivers and streams. Sometimes, they are covered by many feet of very slowly moving or standing water. In very dry years they may represent the only shallow water for miles and their presence is critical to the survival of wetland-dependent species like wood ducks (*Aix sponsa*), river otters (*Lutra iological*), and cottonmouth snakes (*Agkistrodon piscivorus*). Some of the common species of trees found in these wetlands are red maple and pin oak (*Quercus palustris*) in the Northern United States, overcup oak (*Quercus lyrata*) and cypress in the South, and willows (*Salix* spp.) and western hemlock (*Tsuga* sp.) in the Northwest. Bottomland hardwood swamp is a name commonly given to forested swamps in the south central United States.

Fig.2.1: A forested swamp is dominated by trees with emergent vegetation.

Shrub swamps: are similar to forested swamps, except that shrubby vegetation such as buttonbush, willow, dogwood (*Cornus* sp.), and swamp rose (*Rosa palustris*) predominates. In fact, forested and shrub swamps are often found adjacent to one another. The soil is often water logged for much of the year, and covered at times by as much as a few feet of water because this type of swamp is found along slow moving streams and in floodplains. Mangrove swamps are a type of shrub swamp dominated by mangroves that covers vast expanses of southern Florida.

2.2.3 Examples of Swamps Areas

United States: The most famous swamps in the United States are the Everglades, Okefenokee Swamp and the Great Dismal Swamp. Swamps are often called bayous in the southeastern United States, especially in the Gulf Coast region. In the USA, swamps are including a large amount of woody vegetation. However, in Africa swamps are dominated by papyrus. By contrast a marsh in the USA is a wetland without woody vegetation, or elsewhere, a wetland without woody vegetation which is shallower and has less open water surface than a swamp. A mire (or quagmire) is a low-lying wetland of deep, soft soil or mud that sinks underfoot.

Great Dismal Swamp: is located in northeastern North Carolina and southern Virginia. It is a mixture of waterways, swamps and marshes (Figure 2.2). Unlike most swamps, it is not located near a river. It is a coastal plain swamp. Trees like cypress, black gum, juniper, and water ash are common. Animals commonly found in the Great Dismal Swamp include black bears, white-tailed deer, opossum, raccoons, cottonmouth snakes.

Fig.2.2: Skunk Cabbage (Symplocarpus foetidus) sprouts very early in the spring, melting the surrounding snow.

Cypress Swamps: are found in the southern United States (Figure 2.3). They are named for the bald cypress tree. Bald cypress trees are deciduous trees with needle-like leaves. They have very wide bases and "**knees**" that grow from their roots and stick up out of the water. Bald cypress trees can grow to 100 to 120 feet tall. Fire plays an important role in the establishment of bald cypress swamps. Cypress trees grow very quickly after a fire and re-establish themselves before other trees have a chance to grow! Many of the bald cypress trees in cypress swamps in the U.S. were cut down in the late 1800s and the early 1900s. The wood from the bald cypress is resistant to rot and was a popular wood for building. Other trees and shrubs like pond cypress, black gum, red maple, wax myrtle, and buttonwood can also be found in cypress swamps. Animals like white-tailed deer, minks, raccoons, anhingas, pileated woodpeckers, purple gallinules, egrets, herons, alligators, frogs, turtles and snakes are often found in cypress swamps.

U.S. Fish and Wildlife Service U.S. Fish and Wildlife Service

Fig.2.3: Examples of Cypress Swamps in USA

Okefenokee Swamp: Is located in southeastern Georgia and northern Florida (Figure 2.4). It is about 25 miles wide and 40 miles long. Not all of the Okefenokee is a swamp part of it is a bog. In fact, Okefenokee is an Indian word that means "*Land of the Trembling Earth.*" Parts of the swamp are so boggy that you can shake the trees by stomping on the ground. Trees in the Okefenokee Swamp include giant tupelo and bald cypress. Mammals like the raccoon, black bear, white-tailed deer, bobcats, red fox and river otter make the swamp their home. Reptiles in the swamp include the eastern diamondback rattlesnake, cottonmouth, eastern coral snake, copper head, alligator and snapping turtle. Birds like the barred owl, anhinga, great egret, great blue heron and sandhill crane are also found in the swamp. Plants like the pitcher plant, water lily and iologi moss that grow in the swamp can survive in the nutrient poor soil and acidic soil of the Okefenokee swamp.

Fig.2.4:Examples of Okefenokee Swamp

Asia- Asmat Swamp: is a wetland on the southern coast of New Guinea, located within what is now the Indonesian province of Papua. It is sometimes claimed to be the largest alluvial swamp in the world, it has an area of around 30,000 km². It is crossed by numerous rivers and streams, and large areas are underwater at high tide. Ecologically, the swamp is diverse. The muddy coastal areas are dominated by mangroves and nipah palms. Inland, where the swamp is fresh water, other sorts of vegetation become more common, herbaceous vegetation, grasses, and forest. A significant portion of the swamp is peat land. It is home to a wide variety of animals, including freshwater fish, crabs, lobsters, shrimp, crocodiles, sea snakes, and pigeons. Also inhabiting the swamp are large monitor lizards, some longer (although not as heavy) as the more famous Komodo Dragon. The swamp takes its name from the Asmat people, who inhabit it. The difficult terrain of the swamp meant that the Asmat did not have regular contact with outsiders until the 1950s, and the swamp still remains isolated. The swamp forms part of Indonesia's Lorentz National Park.

The Vasyugan Swamp: (Russian: Васюганские болота) is one of the largest swamps in the world, occupying 53,000 km² of western Siberia. The swamp is located in the Novosibirsk, Omsk, Tomsk oblasts of Russia along the left bank of the Ob River. The swamp is a major reservoir of fresh water for the region and several rivers find their sources there. The swamp is home to a number of endangered species which is a concern among local environmentalists as the production of oil and gas has become a major industry in the region.

South America- The Pantanal: is the world's largest wetland area, a flat landscape, with gently sloping and meandering rivers. The region, whose name derives from the Portuguese word "pântano" (meaning "swamp" or "marsh"), is situated in South America, mostly within the Brazilian states of Mato Grosso and Mato Grosso do Sul. There are also small portions in Bolivia and Paraguay. In total, the Pantanal covers about 150,000 square kilometers (58,000 sq mi). The Pantanal floods during the wet season, submerging over 80% of the area, and nurturing the world's richest collection of aquatic plants. It is thought to be the world's most dense flora and fauna ecosystem. It is often overshadowed by the Amazon Rainforest, partly because of its proximity, but is just as vital and interesting a part of the neotropic.

The Paraná Delta: Is the delta of the Paraná River in Argentina. The Paraná flows north south and becomes an alluvial basin (a floodplain) between the Argentine provinces of Entre Ríos and Santa Fe, then emptying into the Río de la Plata. The Paraná Delta has an area of about 14,000 km² and starts to form between the cities of Santa Fe and Rosario, where the river splits into several arms, creating a network of islands and wetlands. Most of it is located in the jurisdiction of Entre Ríos, and parts in the north of Buenos Aires.

Africa- Bangweulu: Is one of the world's great wetland systems, comprising *Lake Bangweulu,* the *Bangweulu Swamps* and the *Bangweulu Flats* or floodplain. Situated in the upper Congo River basin in Zambia, the Bangweulu system covers an almost completely flat area roughly the size of Connecticut or East Anglia, at an elevation of 1140 m straddling Zambia's Luapula Province and Northern Province. It is crucial to the economy and biodiversity of northern Zambia, and to the birdlife of a much larger region, and faces environmental stress and conservation issues. With a long axis of 75 km and a width of up to 40 km, Lake Bangweulu's permanent open water surface is about 3000 km², which expands when its swamps and floodplains are in flood at the end of the rainy season in May. The combined area of the lake and wetlands reaches 15,000 km². The lake has an average depth of only 4 m. The Bangweulu system is fed by about seventeen rivers of which the Chambeshi (the source of the Congo River) is the largest, and is drained by the Luapula River.

The Okavango Delta (or **Okavango Swamp**)**:** In Botswana, is the world's largest inland delta. The area was once part of Lake Makgadikgadi, an ancient lake that dried up some 10,000 years ago. Today, the Okavango River has no outlet to the sea. Instead, it empties onto the sands of the Kalahari Desert, irrigating 15,000 km² of the desert. Each year some 11 cubic kilometers of water reach the delta. Some of this water reaches further south to create Lake Ngami. The water entering the delta is unusually pure, due to the lack of agriculture and industry along the Okavango River. It passes through the sand aquifers of the numerous delta islands and evaporates/transpirates by leaving enormous quantities of salt behind. These precipitation processes are so strong that the vegetation disappears in the center of the islands and thick salt crusts are formed. The waters of the Okavango Delta are subject to seasonal flooding, which begins about mid-summer in the north and six months later in the south (May/June). The water from the delta is evaporated relatively rapidly by the high temperatures, resulting in a cycle of cresting and dropping water in the south. Islands can disappear completely during the peak flood, and then reappear at the end of the season.

The Sudd: Is a vast swamp formed by the White Nile in southern Sudan (Figure 2.5). Its size is variable, but during the wet season it may be over 130,000 km² in area. In the Sudd, the river flows through multiple tangled channels in a pattern that changes each year. Papyrus grows in dense thickets in the shallow water, which is frequented by crocodiles and hippopotami. Sometimes the matted vegetation breaks free of its moorings, building up into floating islands of vegetation up to 30 km in length. Such islands, in varying stages of decomposition, eventually break up. The sluggish waters are host to a large population of mosquitoes and parasites that cause waterborne diseases. The Sudd is considered to be nearly impassable either overland or by watercraft. The early explorers searching for the source of the Nile experienced considerable difficulties, sometimes taking months to get through. In the White Nile, Alan Moorehead says of the Sudd, "there is no more formidable swamp in the world."

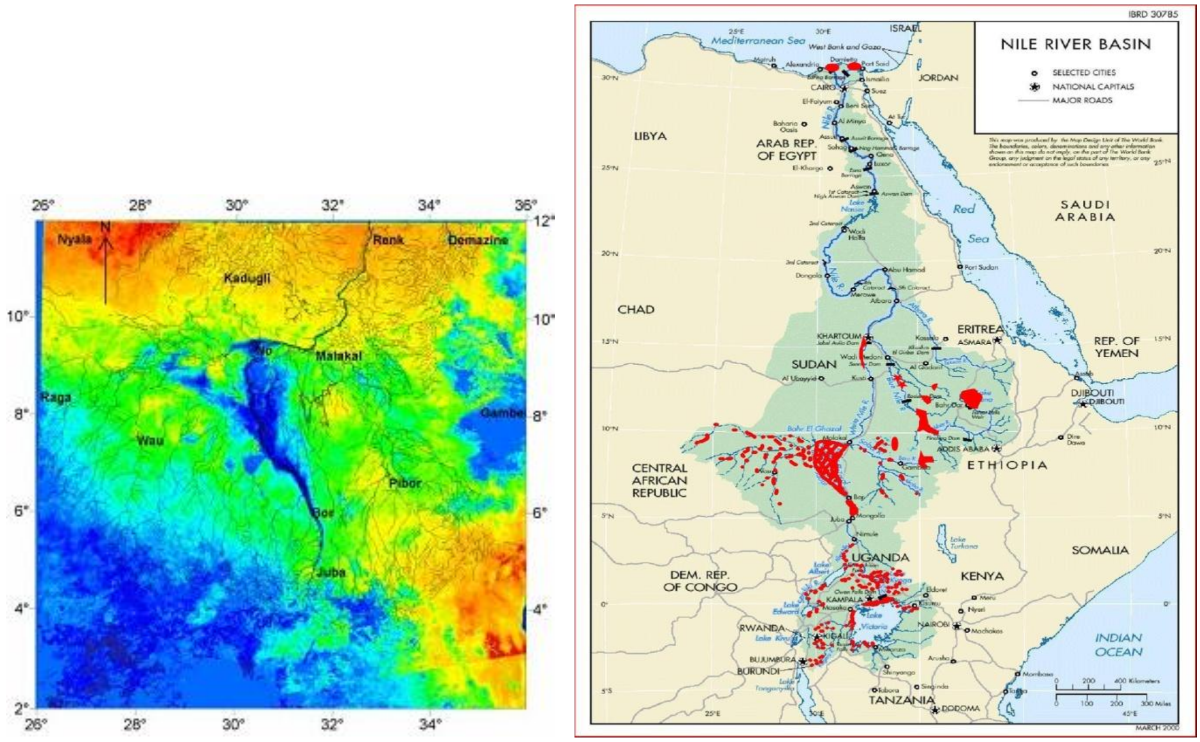


Fig.2.5: Location of the Sudd in southern Sudan.

There are three main waterways through the swamp; the Bahr al Zaraf ("River of the Giraffes"), Bahr al Ghazal ("River of the Gazelles"), and the Bahr al Jabal ("River of the Mountain"), which is the main connection to the Mountain Nile. Because of the Sudd swamp, the water from the southwestern tributaries (the Bahr el Ghazal system) for all practical purposes does not reach the main river and is lost through evaporation and transpiration (Figure 2.6). Hydrogeologists in the early part of the 20th century proposed digging a canal east of the Sudd which would divert water from the Bahr al Jabal above the Sudd to a point farther down the White Nile, bypassing the swamps and carrying the White Nile's water's directly to the main channel of the river. The Jonglei canal scheme was first studied by the government of Sudan in 1946 and plans were developed in 1954-59. Construction work on the canal began in 1978 but the outbreak of political instability in Sudan has held up work for many years. By 1984 when the Southern Sudanese rebels (SPLA) brought the works to a halt, 240km of the canal of a total of 360km had been excavated. It is estimated that the Jonglei canal project would produce 4.8 x 109 m³ of water per year. There are, however, complex environmental and social issues involved, which may limit the scope of the project in practical terms.

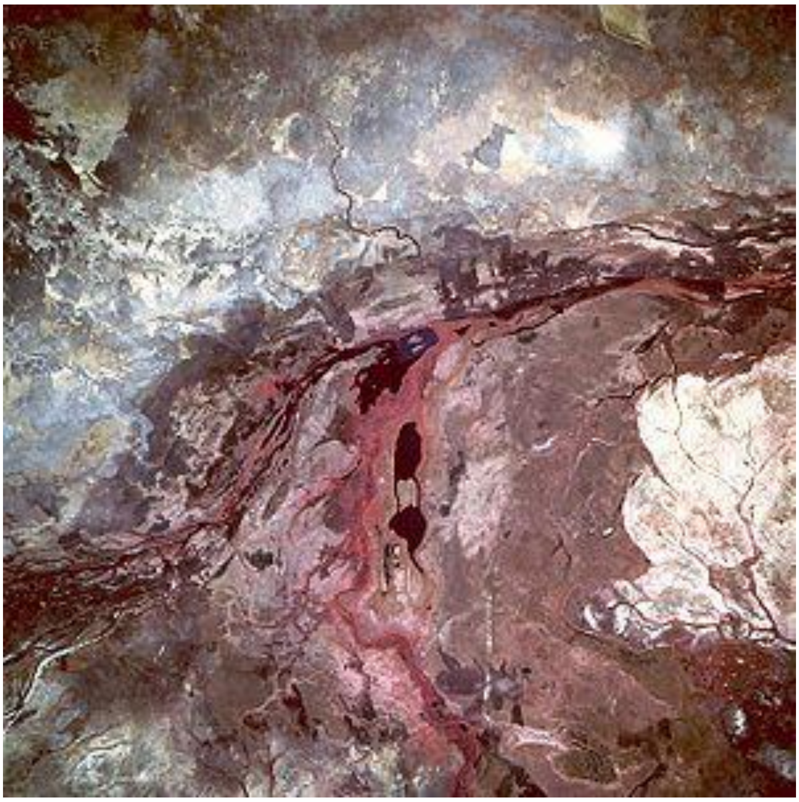


Fig.2.6: Sudd Swamp from space, May 1993 (This photograph was taken during the driest time of year—summer rains generally extend from July through September)

2.3 Modeling of swamps

2.3.1 Hydrological models

Doyle, 2009, conducted an ecological field and modeling study to examine the flood relations of backswamp forests and park trails of the flood plain portion of Congaree National Park, S.C. Continuous water level gages were distributed across the length and width of the flood plain portion referred to as "Congaree Swamp". To facilitate understanding of the lag and peak flood coupling with stage of the Congaree River, a severe and prolonged drought at study start in 2001 extended into late 2002 before backswamp zones circulated floodwaters. Water levels were monitored at 10 gaging stations over a 4-year period from 2002 to 2006. Historical water level stage and discharge data from the Congaree River were digitized from published sources and U.S. Geological Survey (USGS) archives to obtain long-term daily averages for an upstream gage at Columbia, S.C., dating back to 1892. Elevation of ground surface was surveyed for all park trails, water level gages, and additional circuits of roads and boundaries. Rectified elevation data were interpolated into a digital elevation model of the park trail system. Regression models were applied to establish time lags and stage relations between gages at Columbia, S.C., and gages in the upper, middle, and lower reaches of the river and backswamp within the park. Flood relations among backswamp gages exhibited different retention and recession behavior between flood plain reaches with greater hydroperiod in the lower reach than those in the upper and middle reaches of the Congaree Swamp. A flood plain inundation model was developed from gage relations to predict critical river stages and potential inundation of hiking trails on a real-time basis and to forecast the 24-hour flood. In addition, tree-ring analysis was used to evaluate the effects of flood events and flooding history on forest resources at Congaree

National Park. Tree cores were collected from populations of loblolly pine (Pinus taeda), baldcypress (Taxodium distichum), water tupelo (Nyssa aquatica), green ash (Fraxinus pennslyvanica), laurel oak (Quercus laurifolia), swamp chestnut oak (Quercus michauxii), and sycamore (Plantanus occidentalis) within Congaree Swamp in highand low-elevation sites characteristic of shorter and longer flood duration and related to upriver flood controls and dam operation. Ring counts and dating indicated that all loblolly pine trees and nearly all baldcypress collections in this study are post settlement recruits and old-growth cohorts, dating from 100 to 300 years in age. Most hardwood species and trees cored for age analysis were less than 100 years old, demonstrating robust growth and high site quality. Growth chronologies of loblolly pine and baldcypress exhibited positive and negative inflections over the last century that corresponded with climate history and residual effects of Hurricane Hugo in 1989. Stemwood production on average was less for trees and species on sites with longer flood retention and hydroperiod affected more by groundwater seepage and site elevation than river floods. Water level data provided evidence that stream regulation and operations of the Saluda Dam (post-1934) have actually increased the average daily water stage in the Congaree River. There was no difference in tree growth response by species or hydrogeomorphic setting to pre-dam and post-dam flood conditions and river stage. Climate-growth analysis showed that long-term growth variation is controlled more by spring/ summer temperatures in loblolly pine and by spring/summer precipitation in baldcypress than flooding history.

Cynthia et al., 2002, developed a swamp hydrologic model to describe the spatial and temporal distribution of the swamp hydrologic environment. The Okefenokee Swamp is a 160,000 ha freshwater wetland in Southeast Georgia, USA, was divided into 5 sub-basins that reflect similar seasonal hydrodynamics but also indicate local conditions unique to the basins. Topographic gradient influences water-level dynamics in the western swamp (2 sub-basins), which is dominated by the Suwannee River floodplain. The eastern swamp (3 sub-basins) is terraced, and the regional hydrology is driven less by topographic gradient and more by precipitation and evapotranspiration volumes. The relatively steep gradient, berm and lake features in the western swamp's Suwannee River floodplain limit the spatial extent of the Suwannee River sill's effects, whereas system sensitivities to evapotranspiration rates are more important drivers of hydrology in the eastern swamp.

Xingchuan et al., 2002, presented a multi-scale model to simulate the impact of hydrologic changes on the regeneration of a cypress swamp in southern Illinois. This model, SISM (Southern Illinois Swamp Model), captures three processes that operate at different spatial and temporal scales: cypress seed dispersal and germination, seedling growth and mortality, and the succession of saplings and mature trees. In SISM, the life history of cypress is represented in a coherent manner, spatial-temporal scales are related to different life phases, processes are consistently integrated, and the interactions amongst the multiple processes are effectively simulated. Three scenarios reflecting water management alternatives were tested and discussed. The results show that (1) the modeling output under current water variability is comparable with various field studies, (2) a stable hydrologic scenario restricts the spatial distribution of cypress, and (3) a more variable hydrologic regime does not necessarily result in a wide regeneration of cypress.

In early 2001, the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA or Breaux Act) Task Force approved a project that will return a minimum of 1,500 cubic feet/second(cfs) Mississippi River flow to the Maurepas Swamp, restoring swamp hydrology, increasing sediment and nutrient loading, and reinvigorating the Maurepas Swamp. Over 36,000 acres of wetlands will benefit from this re-introduced river flow. The Environmental Protection Agency (EPA) was the lead federal agency for the Maurepas project. Researchers at Louisiana State University completed studies of hydrology (water movement), water quality, and ecology of the Maurepas Swamps. The group developed a sophisticated computer model of hydrology to answer additional questions about the possible effects of reintroduction of Mississippi River water into the swamps. This model concluded that reintroducing Mississippi River water will reduce salt water intrusion into the swamps, which can kill or weaken the cypress and tupelo trees. The model also reinforced earlier predictions that nutrients in the river water would be almost completely taken up in the swamp before the water reaches Lake Maurepas- in turn, supporting the earlier prediction that reintroduction of Mississippi River water would not cause algal blooms in Lake Maurepas. The researchers also developed a new computer ecological model of the swamp, called SWAMPSUSTAIN. The model estimates the time it will take a reintroduction of Mississippi River water into the swamp to result in target swamp elevations considered necessary for long-term sustainability of the swamp. The model predicts that between 5,000 and 10,000 acres of the Maurepas swamp can be restored to sustainability within 50 years if average yearly diversion discharges greater than 1,000 cfs are maintained.

Schaake, J.C., et al., 1999, developed a hydrological swamp model for the two large swamps exist in the basin, i.e. Bahr el Jebel and Machar (Sobat River Basin) swamps, which do not fit in the concept of the gridded model that is being used in the rainfall-runoff hydrological modeling system in the Nile Forecast Center (NFC), and are therefore modeled in the NFC by a swamp model. The concept of the swamp model was developed by Sutcliffe, 1987. The model treats river and adjoining swamps as separate reservoirs, with overflow from river to swamp. The models contain several estimated parameters. They are swamp capacity and surface area, recharge, threshold level on channel inflow for channel loss to occur, and maximum possible outflow from channel. It is essential for better calibration of this model to have concurrent data on inflow, outflow and areal extent of channel and swamp for different times in the year.

Mohamed et al., in 1999 conducted a regional climate model to the Nile Basin, with a special modification to include routing of the Nile flood over the Sudd. The impact of the wetland on the Nile hydroclimatology has been studied by comparing two model scenarios: the present climatology, and a drained Sudd scenario. The results indicate that draining the entire Sudd has negligible impact on the regional water cycle (atmospheric moisture fluxes, precipitation, evaporation, runoff and sub-surface storage) and insignificant compared to the inter-annual variability of these parameters. In terms of mass balance, the Sudd evaporated volume is a small fraction relative to the oceanic moisture in the region (less than 1% of the atmospheric moisture in the Nile Basin). However, the drained Sudd may create some climatic disturbances, which generate slightly higher rainfall than the present situation. This is most likely attributed to an enhanced convective activity that occurs over the dried wetlands. During the wet season the influence of the Sudd is not noticed. In the dry season, when the Sudd may cause the largest impact on the water cycle, there is no mechanism for rainfall, at least in major parts of the basin. The net gain of the Nile water by draining the entire Sudd wetland would be an additional ~ 36 Gm3/yr (higher than observed Nile losses over the Sudd of 29 Gm3/yr). This is about half the long-term mean of the Nile natural flow at Aswan. The famous Jonglei canal phase I would drain about 30% of the Sudd wetland and save about 4 Gm3/yr (5% of the Nile flow at Aswan). The runoff gain would then be up to ~ 36 Gm3 /yr. However, the impact on microclimate is large. The relative humidity will drop by 30 to 40% during the dry season, and temperature will rise by 4 to 6°C. The microclimate impact is confined to the Sudd area and the adjacent area to the west and southwest direction influenced by the wind pattern in the dry season. During the wet season the impact of the Sudd drainage is small, because the surrounding area is already saturated by the rain. However, a slight decrease of relative humidity (<10%) is detected over the Sudd in the wet season.

Bauer, et al., developed a hydrological model for the Okavango Delta based on a finite difference formulation of the relevant flow processes (surface and ground water) modeling software MODFLOW (McDonald and Harbaugh, 1988). Spatially distributed input data include rainfall, evapotranspiration and micropotography. The model results were compared to flooding patterns derived from remote sensing. It has been shown that the flooding dynamics of the Okavango Delta can in principle be understood and modeled in the framework of the two layer finite difference flow model. Results showed that, once the model was calibrated and validated, it could be used to assess the impacts of different management scenarios on the hydrological system. The model is particularly useful to study long-term changes that result from different development scenarios.

Sutcliffe and Parks, 1987, developed a simple reservoir model for the swamps of the Sudd that is responsible for the loss of much of the Nile outflow from Lake Victoria. At present only half of the inflow of the Bahr el Jebel or White Nile at Mongalla emerges from the tail of the swamps. The developed model used measured inflows and outflows and estimates of rainfall and evaporation to reproduce volumes and areas of flooding over the historical period 1905-1980. Predicted outflows based on inflows are then substituted for measured outflows so that the proposed diversions through the Jonglei Canal can be incorporated in the model in order to predict the effects of the canal on areas of flooding.

Georg Petersen, 2008, described the hydrology of the Sudd swamps in southern Sudan. The study comprised a hydrologic investigation and evaluation of the Sudd water balance. The study improved historical interpretations and unveiled 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 was 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 were 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 had 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 were 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 was responsible for area flooding while no return flow occured and drying was 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 provided previously unavailable flow data at Mongalla, the entry to the Sudd swamp, with a high level of confidence; data which were 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.

2.3.2 Demand Forecasting Model

Water demand forecasting has become an essential component in effective water resources planning and management. Water forecasts, together with an evaluation of existing supplies, provide valuable triggers in determining when, or if, new sources of water must be developed. The importance of accurate estimates of future water demands and their role in public planning is now well recognized. Water demand models assume various forms. Models can be aggregated into simple and pliable models or disaggregated by region, population, or location. Models also vary in the timeframe of the data included and the breadth of the modeled processes. The demand forecasting model is effectively incorporating changes in the social, economic, and environmental features when predicting future water consumption in a growing region. Numerous factors can directly or indirectly influence water demand. And these factors could be categorized as depicted in Figure 2.7.

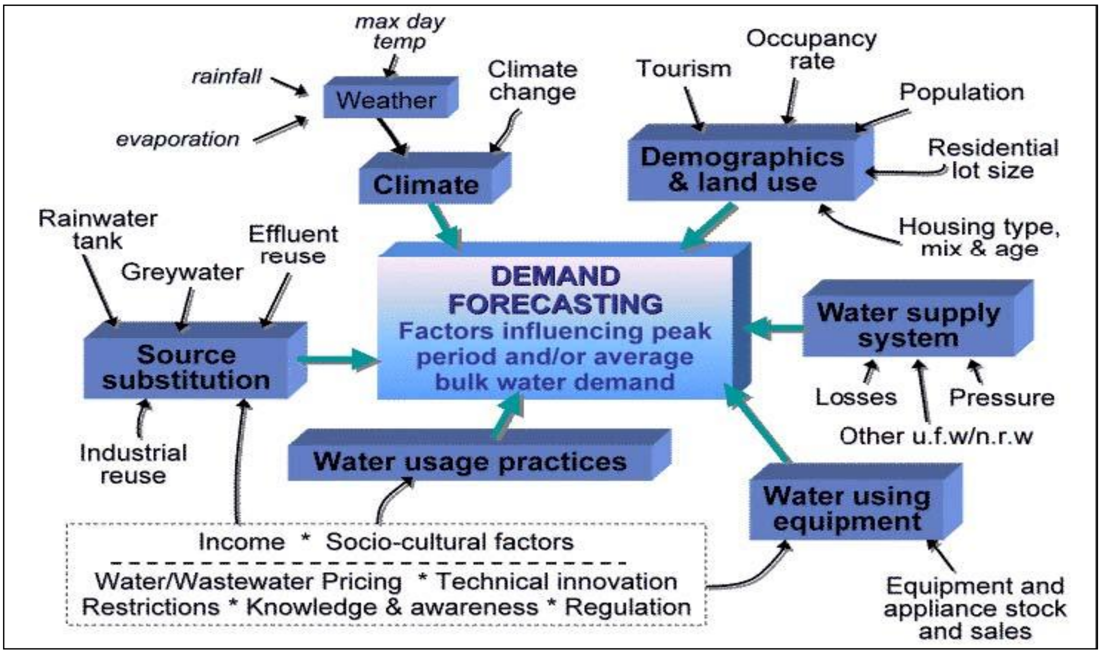


Fig.2.7: Direct and indirect factors influencing water demand

2.3.2.1 Demand Model Applications

Australian Case: A water demand model has been developed for the ACT (Australian Capital Territory) to predict the potential effects of future climate change. It is an aggregated model combining daily water use data from ACTEW with a simple process based model that integrates user behavior with different climate factors (maximum and minimum temperatures, solar radiation, rainfall and vapor pressure). The model approach can separate out climate related demand from base line demand not related to climatic factors. The model has been parameterized for the period 1995-2000 (Figure 2.8) taking into account obvious changes in water use. Validation of the model was carried out against data from earlier years, with results indicating a good fit. This approach provides a significantly better description of water use than an approach using single climate factor alone, such as evaporation. Historical climate files were adjusted to represent climate change scenarios and user behavior adjusted to achieve the same level of utility from the water used. Changes in demand were then expressed as proportions compared with base line usage. The measure of the water-use efficiency for the ACT was based on non-climate driven water demand from 1965 to 2000. The drop in water demand from around 1990 reflects behavioral changes in water use (in this case the switch to grey water for public lands). The modeled versus simulated demand for the ACT for the period 1995 to 2000 was used to calibrate the model. Validation of the model was carried out by determining the goodness of fit of the simulated data to the observed data from 1965 to 1994. The open diamonds represent the calibrated period 1995-2000. A simple water demand model for the ACT based on evaporation room the “best case” to the “worst case”. In addition, mid-range values were calculated from the CSIRO 2001 scenarios (1.25 °C and 3 °C for 2030 and 2070 respectively). For 2030, the anticipated water demand increases from 1% to 5% with a mid-range value of 3%. By 2070 this range has increased to 1% to 16% with a mid-range value of 9%. The range of climate change scenarios presented earlier in this report was used to assess likely changes per capita water demand for the ACT for the years 2030 and 2070.

The full range of possible changes for each time period was assessed by combining the lowest increase in temperature with the largest increase in rainfall and then the highest increase in temperature with the greatest reduction in rainfall. Consequently the demand scenarios range These proportional increases do not take into account the effects of changes in population or water-use behavior. Population growth could be significant for the ACT with mid-range increases of 10% by 2030 and 14% by 2070. Higher range population scenarios are for increases of 30% by 2030 and 84% by 2070. The effect of these population changes are multiplicative with the per capita water demand changes arising from climate change, leading to increased demand when combined. On the other hand, there are a range of possible demand-management strategies which may limit increases in water use. It would be possible using the approach described here to assess the effects of all three factors combined as the method is based on per capita use and can alter user behavior.

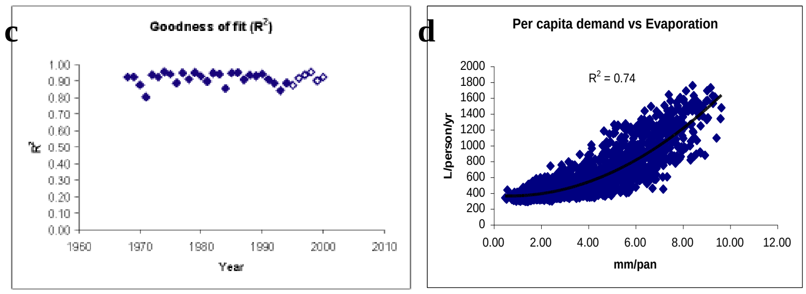


Fig.2.8: Outputs of the modeled water demand for the ACT

The Egyptian case (WDFM Model): The Water Demand Forecasting Model was built within the National Water Quality and Availability Management Project, Component 2000 which is implemented in the MWRI, Planning Sector. There are two forms of the model; the first is a simple form based on Spread (Excel) Sheet with proper links. The second is an Oracle-based Model using the same components of water demand forecasting. The model operates as a standalone, or linked to the Integrated Management Information System (IMIS) of the Planning Sector. In order to have flexibility in developing the water forecasting models, the models are prepared as toolkits with input variability of key model parameters. Effect analyses have been carried out to identify various impacts on water demand forecasts caused by the underlying determinants of consumptions. These effects are represented in the form of ranges of coefficients at the specific year of influence. The coefficients are either positive indicating the relative increase in demand or negative showing a relative reduction in demand. The values of these coefficients are gathered from the literature or past experience and then adjusted to the Egyptian circumstances. Figure 2.9 illustrates the total demand forecast up to 2020.

Tte San Diego Case: The San Diego Country Water Authority (SDCWA or the Authority), like many major water resources agencies, faces a difficult task in forecasting water needs over a long time horizon for a large service population. The water demand forecast typically forms the basis of many decisions concerning the expected amount and timing of expenditures, such as additions to supply and treatment capacity, implementation of water conservation programs, and changes to the structure and level of water prices. Because water demand forecasts are often portrayed by a series of point estimates, external parties can perceive them as if they are entirely accurate and certain. Unfortunately, and by their very nature, such deterministic forecasts do not inform decision-makers of the real uncertainties that are inherent to the forecasting process.

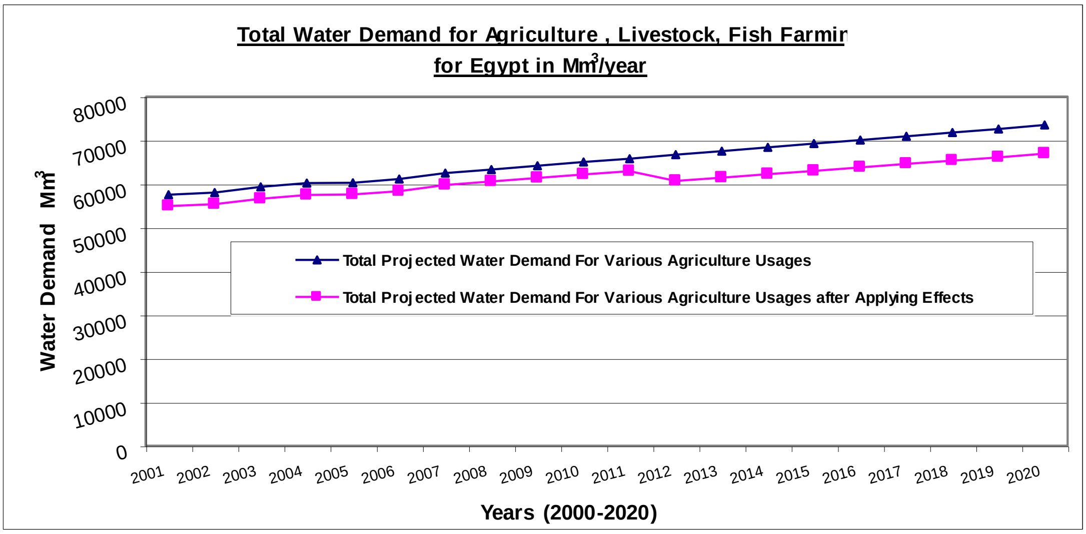


Fig.2.9: Projected Water Demand with Effects for Various Agriculture Water Usages

The presence and magnitude of these uncertainties can and should affect judgments concerning the future. This study develops a probabilistic approach to water demand forecasting that offers the opportunity to quantify and portray forecast uncertainty by improving and expanding upon the Authority's current water demand forecasting procedures to include statistical confidence intervals around its extended long-term forecast (to 2030) of water demand. The SDCWA water forecasting methodology for total demand consists of a system of econometric sector models, each adopting a "rate of use times driver" approach to predict future demands. Sector models differ by their scope of interest (whether single-family, multifamily, nonresidential, or agricultural), their accounting units or driver variables (occupied living units, number of employees, or number of irrigated acres), and their linear regression equations; however, they share common elements.

2.4 Water losses

Heavy losses of water occur in the Sudd region. On the average about half of Bahr El Jebel discharge at Mongalla, before the river enters the swamps is lost when the river emerges from the swamps at Malakal. Due to extensive growth of aquatic vegetable in the Sudd, the influence on evaporation rates was studied to determine the role and contribution of the swamp vegetation to this heavy water loss. Migahid (1948) conducted tank experiments to compare water loss from an open water surface with that from a water surface covered with swamp vegetation. The proportion of water loss from the vegetation covered surface was also compared with that due to transpiration from the plant surface. It was found that the water loss from a water surface covered with papyrus was about three times that from an equivalent open-water surface but only one-third of the loss was attributed to physical evaporation. Transpiration from the plant surface was found to cause two-thirds of the water loss. Water loss due to evaporation was nearly equal, being 9.7 mm/day from open water and 9.8 mm/day from vegetation-covered surfaces. In an earlier series of experiments the rate of evaporation during the month of March for six successive years from 1926-32, was measured from a papyrus tank and a Piche evaporimeter. Hurst (1952) found, from a series of the records, that the best measure of evaporation rate from open water surface is to take the mean value of Piche evaporimeter from several stations in a given area and then average them. In the literature there is no evidence to indicate a special role of swamp vegetation in water loss from vegetation-covered surfaces as in the case of the Sudd. Penman (1963), for example, maintains that "transpiration from papyrus and evaporation from the open lagoon are nearly equal" Rijks (1969) found that evaporation from a papyrus swamp in Uganda was 60+ 15% of evaporation from an open water surface. The amount of water lost in the swamps was determined from careful and extensive hydrological records of river level and discharges upstream and downstream of the swamps (Tottenham, 1913). The study was prompted by a report in 1904 (Garstin, 1904). The study of water losses, conducted over a period of seven years 1905-06 to 1911-12, was directed to determine the percentage loss in the mean discharge of Bahr el Jebel entering Mongalla, before it enters the swamp, and at Malkal after it has emerged from the swamps. The percentage losses of Mongalla discharge was determined as the mean losses per year, losses during June-November when the river is in flood, losses from December-May when the rivers is falling, losses in the month of the highest and the month of the lowest discharge, and the losses in the highest 10 day period of discharge and the lowest 10 days. These losses are given in Tables 2.1 and 2.2.

Table 2.1: Sudd mean losses in the highest and lowest months of the year. Mean discharge in m3/sec. (source: Tottenham, 1913)

	Mean discharge			
Year	**Mongalla**	**Malakal**	**%loss**	**Month**
		a) Highest month of the year		
1906	1918	453	76	September
1907	1386	435	68	September
1908	1326	498	62	August
1909	1613	591	63	September
1910	1675	424	75	September
1911	967	384	60	September
1912	1175	431	63	September
Mean	1437.42	459.42	66.71	
		b) Lowest month of the year		
1906	1027	512	50	March
1907	1016	507	50	March
1908	770	448	42	April
1909	756	464	38	March
1910	744	517	31	March
1911	649	439	24	March
1912	523	427	18	March
Mean	783.57	481.14	36.14	

From the above data it can be concluded that around 500 m^3/sec emerges at the tail with no concern to the amount of water passing Mongalla. It is also concluded that the greater the volume of water passing Mongalla the greater the percentage loss will be. As the discharge passing Mongalla increases, so does the water level in the river channels. As the water reaches bankfull discharge it cannot raise anymore, and consequently cannot travel any further to the northern end of the swamp.

Table 2.2: The budget of Jonglei Canal as an average discharge, year (1960). Mean monthly discharge (x 106 m3) and benefits. Source Jonglei Phase I, executive organ for the development projects in Jonglei area, 1975.

Month	Mongalla	Jonglei	Canal	JEBEL And	Zeraf	Total	Daily Gain	Monthly Benefit
January	52.6	53.4	19.0	32.0	51.0	73.5	13.5	418.5
February	51.3	47.8	19.0	27.6	46.6	35.8	10.8	304.0
March	54.3	46.8	19.0	23.0	42.0	34.4	7.6	236.0
April	61.1	49.4	19.0	22.0	41.0	34.1	6.9	207.0
May	67.3	55.5	19.0	24.0	43.3	34.9	8.4	260.0
June	61.9	60.7	19.0	28.9	47.9	36.4	11.6	348.0
July	71.2	56.2	19.0	31.8	50.8	37.5	13.3	412.0
August	80.7	64.0	19.0	29.2	48.2	36.4	11.8	366.0
September	88.1	71.0	19.0	33.1	52.1	38.1	14.0	420.0
October	89.6	76.2	19.0	35.2	54.2	39.6	14.6	453.0
November	78.3	77.2	19.0	36.4	55.4	40.6	14.8	444.0
December	65.9	69.2	19.0	36.6	55.6	40.7	14.9	462.0
Mean Annual Benefit at Malkal = 4.33 $x10^9$ m^3								

Mean Annual Benefit at Malkal = 4.33 $x10^9$ m^3 will be divided equally between Egypt and Sudan who will share the cost of the project. Sudan's share, measured at Malakal will be 2.35 x 10^9 m^3. As a result of the diversion, in an average year, downstream of the canal takeoff, the water levels of Bahr el Jebel will be reduced by about 29 cm during the flood in September (average level 26.86 m) and by 70 cm during the low season in March (average level 26.46 m). The levels of Bahr El Zeraf will be reduced by 21 cm during the flood (average level 26.68 m) and by 40 cm during the low season (average level 26.40 m). Table 2.2 is comparing the original (1936), the Equatorial Nile canal (1948) and the present (1974) versions of Jonglei Canal. The comparison indicates the main differences between the three status. A number of studies were conducted to estimate evaporation losses from the Sudd area. The summary of these studies is illustrated in table 2.3.

Table 2.3: Summary of evaporation losses in Sudd Marshes area

Evaporation (mm/yr)	Average Sudd Area (Gm^2)	Source	Method
1,533	7.2	Butcher, 1938	Measurement of Papyrus grown water tank, aerial photo, water balance
	8.3	Hurst and Black 1931	Water balance and limited surveys
2,400		Migahid, 1948	Lysimeter experiment on the Sudd close to Bahr el Zeraf cuts
2,150	21.1	Sutcliffe and Parks, 1999	Water Balance
1,636	38	Mohamed, A. Y. 2005	Remote Sensing and SEBAl

2.5 Climate Change

Climate variations and change, caused by external forcing, come as a result of human activities, such as the emission of greenhouse gases or land-use change. Therefore, one has to rely on carefully constructed scenarios of human behavior and activities and determine climate projections on the basis of such scenarios. However human activities are not considered the only part of the reality that determines weather and climate. The growth, movement and decay of weather systems depend also on the vertical structure of the atmosphere, the influence of the underlying land and sea and many other factors not directly experienced by human beings. To understand the climate and its variations we must understand the climate system, the system consisting of various components, including the dynamics and composition of the atmosphere, the ocean, the ice and snow cover, the land surface and its features, the many mutual interactions between them, and the large variety of physical, chemical and biological processes taking place in and among these components. The climate system is an interactive system consisting of five major components, the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the Sun. Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behavior, they are all linked by fluxes of mass, heat and momentum. Climate variations, is not only result from radiative forcing, but also from internal interactions between components of the climate system. A distinction can therefore be made between externally and internally induced natural climate variability and change. Regional or local climate is generally much more variable than climate on a global scale because regional or local variations in one region are compensated for by opposite variations elsewhere.

Human activities, in particular those involving the combustion of fossil fuels for industrial or domestic usage, and biomass burning, produce greenhouse gases and aerosols which affect the composition of the atmosphere. The emission of chlorofluorocarbons (CFCs) and other chlorine and bromine compounds has not only an impact on the radiative forcing, but has also led to the depletion of the stratospheric ozone layer. Land-use change, due to urbanization and human forestry and agricultural practices, affect the physical and 20iological properties of the Earth's surface. Such effects change the radiative forcing and have a potential impact on regional and global climate to which the climate system must act to restore the radiative balance. Heat is trapped in the atmosphere through the greenhouse gases which consists of water vapor, carbon dioxide, methane and nitrous oxide. The hydrological cycle continuously replenishes the world's water resources and is the foundation of life on earth. Human activities are having disturbing influence on the cycle. Therefore understanding short and long term climate change is the key element in defining the extreme climate events like floods and draughts.

2.5.1 Future Expectation

The global annual emission of carbon dioxide from burning fossil fuel and other industrial processes is estimated to have increased from about Gitatonnes of Carbon (GtC) in 1860 to almost 10 GtC by the end of the 20th century. Over the same period, the atmospheric concentration of Carbon dioxide has increased from about 280 parts per million by volume (ppmv) to about 369 ppmv and the global temperature of the earth has increased by about 0.6^{o} C in the past 100 years, and is predicted to continue to rise. Based on assessment of a number of future emissions scenarios of greenhouse gases and aerosols, the intergovernmental Panel on climate change (IPCC) has projected that by the year 2100:

- An average global warming of 0.7 to 2.5 ^{o} C by 2050 with greater warming at higher latitudes (IPCC 2001; Hennessy et al., 2002; Root et al., 2003). The globally averaged surface temperature will warm by 1.4 to 5.8^{o} C (relative to 1990)
- Global mean sea level will rise by 9 to 88 cm (relative to 1990).
  This projection is made up about half by thermal expansion of sea water, about one quarter from melting of glaciers, and a small positive contribution from Greenland ice melt and possibly a negative contribution from snow accumulation over Antarctica. However, the contribution from Antarctica is especially uncertain, with recent events on the Antarctic Peninsula raising the possibility of an earlier positive contribution from the West Antarctic Ice Sheet (WAIS).
- Precipitation will likely increase over the northern mid to high latitudes and Antarctica in winter
- Extreme events (drought, tropical, cyclone intensity) are likely to increase over some areas
- There will be significant changes to snow cover and ice extent
- A weakening of the large-scale-density-driven circulation in the ocean could be evident

These scenarios were regarded as plausible by the IPCC, but not assigned any probabilities. While recent criticism of the technical basis of these scenarios is being considered by the IPCC, it is likely that future projections will lie in roughly the same range, with values near the middle of the range being more probable.

Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC TAR) was published in 2001. The TAR concluded that global warming has taken place over the last century, and there is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities. It is likely that the 1990s was the warmest decade in the last 1000 years, at least in the Northern Hemisphere. Other observations are consistent with this observed warming, including a rise in global average sea level and ocean heat content, and decreases in snow cover and ice extent both in mountain glaciers and Arctic sea ice. Recent evidence suggests that a predicted slow-down in the deep ocean circulation driven by variations in temperature and salinity may also be occurring. The TAR stated that it is likely there will be higher maximum temperatures and heat indices over many land areas, and reduced frequency of low temperatures, including frosts. More intense precipitation events are likely over many mid- to high-latitude land areas. Increased summer continental drying and associated risk of drought are likely in mid-latitudes. Tropical cyclones are projected to become more intense with higher peak winds and rainfall intensities. Other patterns of climate variability, including the El Nino-Southern Oscillation (ENSO), may vary in intensity and frequency, with some climate models suggesting more El Nino-like average conditions, and others no change. Time lags in the ocean-atmosphere system mean that climate change, and especially sea level rise, will continue long after stabilization of greenhouse gas concentrations in the atmosphere.

2.5.2 Impact of climate change on water resources

Water is inextricably linked with food security, human health and environmental protection. Rapid population growth, increasing urbanization, industrialization and pollution threaten the sustainability of our water resources. Natural climate variability and human induced climate change add to those threats, particularly in developing countries where the impacts are potentially great and the capacity to cope is weakest. The following subsections are highlights of some impacts on water resources.

2.5.2.1 Hydrological cycle

A significant proportion of the solar energy received by the earth is used in driving the hydrological cycle. Greater greenhouse gas concentrations in the atmosphere mean an increase of the available energy on the surface of the earth and thus according to the basics of thermodynamics, an "intensification" of the hydrological cycle. At the global scale, all climate model simulations have verified this (Kabat et al., 2003). The expected intensification of the hydrological cycle will not be experienced merely as a smooth linear trend, but rather in the form of oscillations (for example ENSO). The oscillations may be more frequent than in the past and the amplitude of the variability may also increase over some areas. The climate changes alter the route and residence time of water in the watershed and change its quality. As a result water might be unsuitable as a resource.

2.5.2.2 Precipitation

The IPCC third assessment report (IPCC TAR) summarizes projected precipitation trends as a general increase in mean annual precipitation in the Northern Hemisphere (Autumn and winter) and a decrease in the tropics and sub-tropics in both hemispheres. The frequency of extreme rainfall is likely to increase with global warming, although the spatial resolution of global climate models is too coarse to provide details. Higher temperatures imply that a smaller proportion of precipitation may fall as snow.

Precipitation changes are more spatially variable than projected temperature changes. Although a general increase in precipitation is expected, some regions will see large increases, while others will see significant reductions. There is still quite a bit of uncertainty about the prediction of precipitation, for two main reasons:

- Precipitation is a secondary process in General Circulation Models (GCMs) and as such, is poorly represented
- Heavy precipitation systems frequently occur on scales that are considerably smaller than the typical grid scale of GCMs, which is two to three degrees of latitude/longitude.

2.5.2.3 Evapo-transpiration

Increased temperatures result in an increase in potential evaporation. In dry regions, potential evaporation is driven by energy and is not constrained by atpospheric moisture contents. In humid regions, however, atmospheric moisture content is a major limitation to evaporation. Studies show increases in evaporation with increased temperatures. Vegetation also plays an important role in evaporation, partially by intercepting precipitation and partially by determining the rate of transpiration. Higher CO_2 concentrations may lead to increased water use efficiency i.e. water use per unit of biomass, implying a reduction in transpiration. However, higher CO_2 concentrations may also be associated with increased plant growth, compensating for increased water use efficiency. Plants may thus acclimatize of evaporation is constrained by water availability.

2.5.2.4 Soil moisture

Runs with the HadCM2GCM show that increases in greenhouse gases are associated with reduced soil moisture in the Northern Hemisphere summers. This is the result of higher winter and spring evaporation, caused by higher temperatures and reduced snow cover, and lower rainfall during the summer. The lower the water holding capacity of the soil, the greater is the sensitivity to climate change.

2.5.2.5 Ground water recharge

Increased winter rainfall may result in increased groundwater recharge in the Northern Hemisphere. However, increased temperatures may increase the rate of evaporation, which leads to longer periods of soil water deficits. Shallow unconfined aquifers along floodplains in semiarid regions are recharged by seasonal stream flows and can be depleted directly by evaporation. Changes of the duration of flow in those streams may lead to reduced groundwater recharge. Sea level rise could cause saline intrusion to coastal aquifers, especially in shallow aquifers. An overlying bed that is impermeable, on the other hand, characteristics a confined aquifer and local rainfall does not influence the aquifer.

2.5.2.6 River flow

Most hydrological studies on the effect of climate change have concentrated on stream flow and runoff. Stream flow is water flowing in a river channel, whereas runoff is defined as the amount of precipitation that does not evaporate. Although there are many hydrological models simulate river flows using climate scenarios derived from GCMs, relatively few studies have been published for Africa, Latin America and South East Asia. Responses in different hydroclimates may be quite different. The following four examples illustrate this:

- Cold and cool temperate climates: Stream flows in these areas are largely dependent on melting snow in spring time. The most important effect of climate change is the timing of stream flow. There will be more runoff during winter because less precipitation falls as snow.
- Mild temperate climates: These regions are dominated by rainfall and evaporation. The magnitude of the flows is determined largely by rainfall changes. Trends show a decrease in summer runoff and an increase in winter runoff.
- Semi arid and arid regions: Here a small percentage of change in rainfall causes considerable effects in runoff
- Tropical regions: runoff responses are largely dependent on rainfall. The number of extreme events causing flooding may increase due to increased in precipitation.

2.5.2.7 Water quality

Agricultural practices may change as a result of climate change. Agriculture chemical loads in surface and groundwater may therefore change accordingly. Furthermore, higher temperatures may decrease the concentration of Oxygen and thus increase eutrophication.

2.5.2.8 Lakes

Closed (endorheic) lakes with no outflow are especially vulnerable to changes in climate conditions. These lakes are considered as good indicators of the effects of climate change. Exorheic lakes may also be sensitive to climate change. For example, levels of lake Victoria in East Africa have increased for several years following increases in precipitation levels.

Observational evidence indicates that climate changes in the 20th century have already affected a diverse set of physical and biological systems. Examples of observed changes with linkages to climate include shrinkage of glaciers; thawing of permafrost; shifts in ice freeze and break-up dates on rivers and lakes; increases in rainfall and rainfall intensity in most mid- and high latitudes of the Northern Hemisphere; lengthening of growing seasons; and earlier flowering dates of trees, emergence of insects and egg-laying in birds. Statistically significant associations between changes in regional climate and observed changes in physical and biological systems have been documented in freshwater, terrestrial and marine environments on all continents except Australia (see Hughes, 2003).

2.5.3 Sea level rise

Melting ice and thermal expansion of the oceans are the two primary drivers of sea level rise. As the sea rises, there are four main impacts that are:

- Increased coastal erosion: Sea level rise, more extreme weather, and a loss of sea ice will contribute to more erosion and flooding along vulnerable Arctic shorelines. Higher sea levels with less ice cover will expose more of the coast to both normal waves and more powerful storm waves.
- Flooding, inundation and displacement of wetlands and lowland: land presently at the margins of tide and wave action may be inundated and accelerated erosion of dunes may occur in response to higher wave action associated with raised water levels.
- Impairment of water quality in freshwater aquifers and estuaries: due to low elevation and small hydraulic gradient, coastal plain groundwater resources of the southeastern United States are potentially vulnerable to salinisation from sea level increase. Saline intrusion in the lower reaches of the deltas would be aggravated by the predicted sea level rise and may warrant revised management of flow control
- Reduced protection from extreme storm and flood events: higher sea levels provide a higher base for storm surges to build on, making severe floods more likely.

2.6 River Nile Climate Studies

Siam, 2010, studied the impact of climate change on the upper Blue Nile catchments flows using the IPCC scenarios. The Upper Blue Nile catchment supplies Egypt with nearly 60% of its annual transboundary share. Meteorological data from three different sources (CRU, University of Delaware and Rain gauges from MWRI) are analyzed and the most accurate is selected for downscaling. Three statistical downscaling techniques (Delta, ANN, Bias-Correction) are investigated for three chosen GCMs (The Canadian CGCM 3.1, the French CNRM-CM3 and the American GFDL-CM2); each tested for the two IPCC scenarios; the mid-high (A2) and the low scenarios (B1). The results of downscaling are used as inputs for the hydrological modeling to predict the upper Blue Nile catchment flows while testing two different approaches; artificial neural network (ANN) and HEC-HMS. The corresponding range of change in flow values is transferred to the High Aswan Dam (HAD) as historically correlated with flows arriving at Roseiras dam (While assuming that patterns for climate change for the Equatorial plateau are similar to those for the Ethiopian plateau) in order to estimate the future change in the Nile flows arriving at Aswan for the remainder of the current century. The results showed a possible decrease by about 20% under the GFDL model and a probable increase by about 40% under the CNRM model both using the A2 scenario.

El.Shamy et al., (2009) used the output of 17 GCMs with the SRES A1B emission scenario to investigate the impacts of climate change on the Upper Blue Nile catchment flows for the period from 2081 to 2098. The temperature and the precipitation are downscaled using the bias-correction approach. The baseline has been selected to be 1961–1990 as this is the period for which most climate centers have submitted daily data for the 20th century climate experiment (20c3m). The observed rainfall dataset has been obtained from the NFS (Nile Forecast System) as gridded daily rainfall for the period 1992-2006. However, these two periods don't overlap; the effect of this difference on the long-term mean water balance has been found to be small as there is little difference in the mean monthly rainfall distribution for the two periods. Changes in total annual precipitation range from −15% to +14% and temperature from 2oC to 5oC and consequently PET to increase by 2-14%. The NFS hydrological model hosted by the MWRI is used to get the corresponding flow of each scenario. The results show that the ensemble mean annual flow at Diem is reduced by 15% compared to the baseline. However, the very high sensitivity of flow to rainfall makes such a number highly uncertain. There is some evidence that higher reductions in rainfall may be accompanied by higher increases in PET possibly due to reductions in cloud cover. This further enhances the effect of rainfall reduction on runoff leading to very high reductions in the mean annual flow for some models (up to 60%). Some models predicted large increases as well (up to 45%).

A more detailed modeling effort was undertaken by Yates and Strzepek (1998) in a climate change assessment for the Nile basin. Lumped hydrologic models and lake/swamp models for the entire Nile system were developed and calibrated on a monthly basis. Six different GCM experiments were used in the assessment. GCM temperature and precipitation changes were interpolated to a 0.5° x 0.5° grid for use with the hydrologic models. GCM projections of Lake Victoria temperature changes ranged from 2 to 2.7° C with precipitation changes between -0.2 to +26%. Blue Nile changes ranged from 2.2 to 3.7°C and -8.8 to +55% for temperature and precipitation, respectively. Modeled Blue Nile flows ranged from -32 to +133%, while Lake Victoria 22 flows ranged from -35 to +104%. The study concluded that river flows were especially susceptible to precipitation changes (Tidwell, 2006).

Conway and Hulme (1996) used three climate scenarios in a study of the sensitivity of Nile river flows to potential climate change. One dry and one wet scenario were selected from GCM experiments, and a third scenario was constructed from a weighted average of seven models. The Composite precipitation scenario was generated from a weighted mean of seven equilibrium GCM change fields (Hulme, 1994). Each GCM was given a weighting based on its ability to simulate current precipitation. The temperature changes were given equal weights in the composite scenario. For measuring the corresponding flows, a hydrological model for the Blue Nile catchment is divided into 10-minute latitude by 10-minute longitude grid cells. Estimates of mean monthly precipitation and evapotranspiration are calculated for all grid cells and fed into a simple monthly water balance. The runoff obtained for each cell is then summed to produce an overall estimate of catchment runoff. The model has three adjustable parameters that are assumed constant for all grid cells except for the cells representing the Lake Tana and Dabus swamp subcatchments. The grid cells in these two subcatchments require different parameter values in order to simulate the storage and delaying effect on runoff from these hydrologically special areas. For Lake Victoria an existing monthly water balance model of the lake catchment was used. Simulated changes in runoff ranged from -8.7 to +15.3% for the Blue Nile and from -9.2% to +11.8% for Lake Victoria, with just one scenario predicting decreases in the two basins. While Lake Victoria demonstrated greater sensitivity to temperature changes than the Blue Nile, the study found that both were more susceptible to changes in precipitation than temperature.

Strzepek and Yales (1996) developed a one dimensional water balance model to investigate the possible impacts of climate change over the whole Nile basin. Three GCMs and hypothetical scenarios based on sensitivity analyses are used. To assess climate change effects, the GCM grids were overlaid on the historic monthly temperature and precipitation surfaces in the GIS. The change in temperature between the l x and 2x CO2 scenarios for each grid cell was considered constant over the cell and was added to the historic value to produce a new temperature surface for that month. The precipitation change (as a ratio of climate change to base values) was overlaid on the historic precipitation surface and then multiplied to produce a new precipitation surface. Catchments' weighted-average climate parameters were calculated from the new temperature and precipitation surfaces. For the sensitivity analyses, spatially homogeneous changes in temperature (+2 and +4oC) and precipitation (±20%) were applied to the reference climate parameters. Two of the GCMs show a decrease in the flow at Aswan by 22% and 77%, the third model shows an increase by 30% relative to the average of the historic values from 1900 to 1972.

Chapter 3. Sudd Natural Resources And Potential Assessment

3.1 Introduction

Sudd marshes have scientific, socioeconomic and political value by the fact that they have a major role in the conservation of biodiversity. The swamps and floodplains of the Sudd support a rich ecosystem, which is essential to the pastoral economy of the local inhabitants. However, the prospective for potential development is still not clearly identified due to the significant knowledge gaps. This chapter introduces the data collection related to different aspects. The main objectives are to develop a GIS based simulation tool for sustainable development of the Sudd marshes. The intended development will be created through development intervention to improve the living conditions of all people in and around the Sudd area, to create alternative livelihoods, to alleviate poverty, to enhance agriculture productivity, and to protect and preserve the biodiversity and environments.

3.2 Origin and description

Sudd word was originally used to refer to the blockage by vegetation as an obstruction to river navigation. It has also become a synonym for permanent swamps. The Sudd area lies between coordinates 6^o 30′ – 9 ^{o} 30′ N and 30 ^{o} 10′ – 31 ^{o} 45′E. It is considered as the largest tropical wetland in the world with an elevation of 350 – 450 m asl. The Sudd area is approximately 5,700 000 ha (246,111 km^2). The Sudd region has, been classified into four land categories according to flood liability of each type. These categories are: High land, intermediate land, toich and Sudd or permanent swamps.

The High Land: The ground elevations are standing no more than a few centimeters above the general terrain. They are scattered ridges in the terrain. They have permeable soil and, because of their elevation, have better drainage. These high lands provide the only refuge for man and animals during the high rainy season where extensive flooding occurs elsewhere.

The Intermediate Land: This is the extensive and flat clay plain lying to the east of Bahr El Zeraf. As the name indicates, the topography of this land is intermediate between that of the high grounds and the toich or water meadows adjacent to river banks. The landscape is a typical expanse of open grassland. During the rainy season they are subject to flooding or at least severe water logging.

During the dry season they are waterless. Sometimes, and as a result of the combination of heavy rainfall and the flatness of the land waves of flood advance across the clay plain. This is referred to as the “creeping flow”.

The Toich: Toich is a local word meaning land seasonally flooded by water spills from rivers (or other water courses) and where the soil retains sufficient moisture during the dry season to support the growth of pasture. They vary in area and type of pasture grass depending on the hydrological conditions of the sustaining river or water channel.

Sudd: This land formation consisting of permanent swamps for the greater part of the year occurs immediately below the toich level. The soils have a thick layer of peat covering mineral soil of alluvial origin.

3.3 The Sudd area and population

It found in three locations as follows:

- A narrow southern belt 10 km wide and 146 km long (Mongalla to Bor). This area is inhabited by the Mundari and the Dinka tribes
- The flat central portion of gradient 1.0-1.5 cm/km. This portion extends from Bor to lake No with the largest width of 40 km and a depth of at least 10 m. This part is inhabited by both the Dinka and the Nuer tribes.
- A narrower northern portion extending from Lake No to the confluence of Bahr el Zeraf within the White Nile of 2 km wide. This portion is inhabited by the Nuer Shilluk and the Dinka tribes.

The Sudd area is prone to seasonal annual flooding (July- December) and highly evaporation volume of water from the extended swamps. As mentioned above the Sudd area is inhabited by three main group or tribes: the Shilluk, Nuer and Dinka. The last two groups include various inter-tribal sections within each tribe. The land of the Shilluk is around and the north of the outfall of the Jonglei canal. The Nuer (Figure 3.1) lives to the south of River Sobat and east Bahr El Zeraf. The southern Dinka country extends north from south of the canal takeoff at Bor to the southern limit of the Nuer country. Both the Nuer and Dinka countries will be traversed by the Jonglei canal. The northern Dinka lives between the Shilluk in the north and the Nuer to the south. The Shilluk land will be only indirectly affected by the canal.

The Shilluk live (Figure 3.2) in villages built on the higher land along the alluvial banks of the White Nile. They changed relatively recently from a predominantly migratory to a more or less sedentary life. They still own livestock but their economy has been extended to crop production and fishing in addition to limited animal production. On the average they own less cattle than the Dinka or Nuer and their livestock consists mainly of sheep. Their livestock husbandry is less elaborate. No cattle camps are normally established as distances between dry season *toich* grazing and the permanent village are short.

The Nuer people are primarily pastoralists and the preoccupation with cattle is the most important feature of their life (Evans-Pritchard, 1940). They on the high lands in homesteads widely separated from each other. Although a limited amount of crop production is practiced, cattle represent a reliable alternative or insurance against crop failure. Fishing represents another economic activity particularly at the beginning and end of the rainy season.

Fig.3.1: The Nuer tribes

The Dinka, like the Nuer, are also primarily pastoralists, but limited crop production and fishing are subsidiary economic activities. It is stated by Deng (1973) that the Dinka are over occupied by their cattle to an extent which limits optimal utilization of the resources of their land. The southern Dinka, south of the Nuer land, lives in villages on high lands more closely settled than those of the Nuer but not as compact as the villages of the Shilluk.

Fig.3.2: Group of Children, Shilluk in Malakal and the Dinka tribes

There are no detailed data on human demography in the area. Recent estimates of the total population living in the area traversed by the Jonglei canal give a total of 260, 740 people, belonging to the Dinka and Nuer groups. The estimate does not include the third group, the Shilluk, since they live strictly outside the Jonglei area and their land is not traversed by the canal. The population density distribution (Table 3.1) in the area increase from north to south with the highest density in the southern Dinka land in Kongor and Bor district.

Despite the variation in human population density between the Dinka and Nuer people whose land will be traversed by the Canal, their mode of life and pattern of land use are very similar and ecologically determined. They migrate with their cattle in rhythmic seasonal movements, the extent of which is determined by the land availability.

Table 3.1: Population distribution in different section in Dinka and Nuer land traversed by the canal. Source: Executive Organ for the Development Projects in Jonglei Area, 1979.

	Subsection		
Section	**Area (km^2)**	**Total population**	**Density per km^2**
A	539	20113	37.50
	3,870	34.234	11.43
	974	8.279	8.50
	4.870	32.045	6.58
	1.002	6.593	6.58
B	1.135	42.5563	37.29
C	483	52.563	109.29
	227	8.513	37.50
	564	1.664	2.90
D	483	52.787	109.29
	403	1.168	2.89
Total	14.550	260.746	17.32

Distribution of High Lands, Intermediate Lands, *toich* grazing and water, except during the rainy season when both human and animal population settle in the permanent villages on the High Lands away from the flooded plains, life for the rest of the year is managed from cattle camps sited in the Intermediate Lands or the *toiches* at various distances from the villages. This annual transhumant migration of people and livestock represents an example of adaptation to the local environment and rational utilization of the grazing resources in the area. The cycle of migration starts from the permanent villages in about November, when the dry season has commenced, with a movement westwards towards the intermediate lands. It ends in May or June, when the river water and the rainy season sets in, with a return movement eastwards to the high lands. The rate of movement in both direction is gradual but is influenced by the availability of grazing and water when moving west towards the river, or by early rising flooding in the *toich* hastening an early eastwards movement through the intermediate land back to the permanent village sites on the high land.

The Shilluk, unlike the Nuer or the Dinka have the Intermediate and *Toich* grazing in the vicinity of their villages, and as a consequence have been able to attend more to cultivation of crops. They cultivate four types of land. Around the homesteads cowpea, gourd, marrow, water melon, tobacco and maize are grown in late May or as soon as sufficient rain has fallen. Quick maturing red-grained sorghum is also planted at about the same time interplant with sesame, and when harvested in August the stalks are allowed to ratoon shifting cultivation is practiced in the intermediate land where a white-grained sorghum, tolerant of flooding, is grown. In the dry season small vegetable plots are established along the alluvial banks of the White Nile, often with irrigation.

3.4 Sudd Marshes natural resources

Ecologically the Sudd wetland (Figure 3.3) encompasses a number of different ecosystems, grading from open water and submerged vegetation, to floating fringe vegetation, seasonally inundated woodland, rain-fed and river-fed grasslands, and floodplain scrubland.

Fig.3.3: Sudd Marshes wetland

3.4.1 Vegetation

Flora is found in five locations:

Open water vegetation: dominated by free floating leaved plants like Eichhoria crassipes, Lemma gibba, azolla nilotica and Nymphaea lotus and submerged vegetation e.g. Potamgeton trapa and cerlolphyllum spp. *Phragmites toiches* are found where soil moisture is available to depth of more than 1 m. The source of moisture here is not the direct river spill as in Echinchola *toiches* but in the river and water courses. The dominant species is *Pharmgmites communis* Trin. With *E. pyramidalia* and *Sorghum lanceolatum*.

Permanent swamps: flooded throughout the year and dominated by Cyperus papayrus, Vossia cuspidate, Pyragmites karka and typha domingensis. In the permanent swamps the vegetation is dominated by *Cyperus papyrus* L. but five components associated with it are distinguishable. These are: (1) a fringing wall of papyrus and other tall species bordering river channels; (2) a tangle of climbers on the fringing wall; (3) aquatic macrophytes and ferns inhabiting the inlets and bays along the banks; (4) sporadic occurrence of woody species, and; (5) water hyacinth inhabiting the slow-moving channels and side-arms of the river where it vegetatively propagates and drifts into the main-stream during high water. The composition of these components is:

Papyrus wall	*cyperus papyrus L.*	
		Vossia cuspidate (Roxb) *W. Griff.*
		Phramgites mauritianus Kunth
Climbers		*Ipomea axuqtic Froxs.*
		carrica (L.) *Sweet*
		*Vigna nilotica (*Del) *Hook f.*
		Luffa cylinderica M. J. Roem
		Cissus ibensis Hook f.
		Helianthus sp.
Macophytes		*Nymphae lotus* L.
		N. coerules Savingy

		Najas pectinata (Parl.) Magnus
		Ottelia ulvifolia (Planch) Walp
		Vallisneria aethiopica fenzl
		Ultricularia thonningii Schumach
		Pistia stratoites L.
		Polygonum sp.
		Ceratophyllum demersum L.
		Trapa bipinosa Roxb
		T. natans
Ferns		*Dryopteris gongyloides*
		Azolla niltica
		Dryopteris gongyloides
	Azola	*nilotica*
Woody plants	*Aeschynomomene elphroxylon*	
		(Guillem, and Perrot.) Taub
Allien plants		*Eichhornia crassipes (Mart.) Solms*

River flooded grassland: dominated by Pyragmites, Sorghum, Hyperhenia and Selaria grasses as well as Oryza and Echinchloa. This is a most productive grassland type for livestock and wild life grazing. Where flooding persists for longer periods as a result of rise in water levels when coupled with the peak of the rains, *Echinochloa toiches* flourish. Here the dominant grass species are *E. stagnina* (Retz) *Beauv. And E. Pyramidalis* (Lam). Hitch. & Chase with *Oryza barthii*(A. Chev.), *O.punctata* and *Vossia cuspidate* (Roxb.) W. Griff. As associates. *E. stagnina and V. cuspidate* generally occur where flooding is longer and deeper and where the soil remains moist during the dry season. *E. pyramidalis* and *Oryza* species are limited to areas where the depth and duration of flooding is less. *Echinochloa toiches* are the only source of reliable green grazing available to livestock during the dry season. The northwestern edge of the region in the swamps of Bahr el Ghazal is characterized by slightly different types of toiches vegetation, referred to as *Hayprhenia toiches*. Here and during the rainy season flooding from rivers and water courses is sporadic and rarely exceeds a continuous period of 10 weeks. In the dry season the water table falls considerably to a level lower than in *Phragmites toiches*. The dominant grass is *Hyparrhenia rufa* (Nees) and Stap. Other species found are *Imperata cylinderica* (L.) Beauv. And *Sporobolous pyramidalis* (Lam.) Hitch.

Rain flooded grassland: this occurs on seasonally logged clay soil usually heavily used by livestock and is dominated by Echinochloa, haplocloda, Sporobulo pyramidalis, phragmites sorghum, Hyperhinia ruffa. In the northern part, where rainfall is relatively less, the ground grass cover is composed of short annual species of *Eragrostis* and *Aristida*. In the southern parts, where rainfall is greater, *Hyperrhenia dissolute* (Nees ex steud) W.D. Clayton and *H. filipendula*(Hochst) Stafvar. *filipendula* are abundant. In the intermediate land the clay soil is generally heavy, impermeable, and waterlogged during the rainy season. These lands are also subject to surface flooding caused by heavy and continuous rains falling on already impermeable soil. The predominated feature of the vegetation is vast open grass plains dominated by *Hyparrheniaa rufa* (Nees) Staf. And *Setaria incrassate* (Hochst) Hack. The former species is found on flooded areas whereas the latter favor areas which receive less flooding. The two types of grassland are found in distinct areas and, as a result, the intermediate lands are sometimes referred to is being a *Hyparrhenia* or *Setaria* type. In the *Setaria* type grassland, associate species include *Ischaemum afrum* (J.F. Gmel.), Dandy, comb. Nov., *Sorghum dimidiatum* Stapf. And species of *Brachiaria, Panicum*, and *Andropogon.* Associated with *Hyparrhenia* grassland type is *Oryza* sp., *Sorghum* sp. And *Sporobolus* sp. *Toich* vegetation is determined by the water level of the river or water course with which it is associated. Vegetation here is generally open grassland with very occasional tree species. The composition of grassland and dominance by species is dependent on soil type and the degree of soil moisture saturation resulting from river level fluctuations. Accordingly three types of grassland vegetation can generally be recognized: *Echinochla toiches, Phragnites toiches* and *Hyparrhenia toiches.*

Woodland: this is a well drained area on higher ground dominated by trees like Acacia seyal, Acacia sieberania and Balantes aegyptiaca. This area is used for settlements and wet season cultivation. In the high lands, the soil is generally lighter and better drained clay which is rarely waterlogged. The vegetation here typically consists of thorn and mixed woodland tree species with a ground cover of grasses. Tree species include: *Acacia seyal* Del. Var. *seyal, A. seyal* del. Var. *fisula* (Schweinf) Olive., *Balanites aegyptiaca* Del., *A. siberiana* Dc. Var. *siberiana, Cadaba farinose* Froks. Subp. *Farinose*, *Salvadora persical* L., palms I *Hyphaene thebarica* (L.) Mart., and *Borassua aethiopium* Mart occur in association with the above species but are also found in pure stands on the higher soils. The ground cover varies according to the locality, but in general the annual grasses predominate. Other types of woodland vegetation occur in the eastern and western limits of the sudd region. The eastern part, toward the Ethiopian formtier, is dominated by stands of *Combretum.* Farther to the west, along the border of the sudd region, with the ironstone plateau in the southwest, there are mixed woodland types of variable composition of deciduous species of *Cambretum, terminalaia, Anogeissus, Acacia, Dalbergia,Kigelia, ficus,* and *Bauhinia.* The area of the high lands is only a small fraction of an otherwise very flat country, and is consequently very heavily population. It is exploited for permanent settlements and cultivation, and consequently pressure on vegetation has been progressively heavy and the original vegetation very much modified.

3.4.2 Distribution of Vegetation

Water depth, current velocity and ground level have been recognized as the most important factors controlling the major species (Migahid, 1947).

Water depth does not limit the growth of *papyrus* or *Vossia*. In deep water *papyrus* culms can rise to the surface and float while the strong and flexible rhizomes of *Vossia* can spread laterally and send aerial branches from the nodes. On the other hand, *Phragmites* and *Typha* do not thrive in deep water as they need to be anchored to a substratum. Floating or submerged aquatic macrophtes can exist in various depths but only the water surface is stagnant or moved slowly. The general occurrence of the climbers follows the fringe wall species with which they are associated. Because of its soft, rhizomes *papyrus* is intolerant of fast moving water.

Current velocity, Migahid (1948) found that the maximum current velocity which papyrus can withstand is 0.028 m/s. *Phragmites* and *Typha* can tolerate current velocities up to 0.129 m/s.

The ground level is perhaps the most important factor affecting the distribution of these species. This is brought about through the indirect effect of ground on availability of moisture and the penetrability of the soil by roots. Deep rooting species such as *Phragmites and Typha* can reach the soil moisture in the higher ground despite the small capillary rise in the impermeable soil. *Papyrus*or and *Vossia* are not found when the ground level is above one meter of the highest level of the river. They are both shallow rooting. The difference in ground level is too small to produce a spectacular alternation of pure stands of *papyrus, Vossia* and *Phramites* along Bahr el Jebel throughout the Sudd (Migahid, 1947and 1952). Ground level also affects penetration of plant roots through its effect on saturation capacity of the soil. When the soil is permanently covered with water, it absorbs an excess and slowly changes into liquid mud which, although offering on resistance to root penetration, does not provide a solid substratum to anchor the roots. Although the soil can turn into liquid mud in the presence excess water, it soon becomes extremely hard upon drying. Most of these plants have delicate undignified roots, and consequently, not only is the soil water content, but also the penetrability of the soil, are considered factors limiting plant growth and distribution. Ground level produces a decrease in soil volume when the saturated clay soil begins to dry. This decrease in volume through shrinkage has physical effects on the growth of plants. Shrinkage produces lateral pressure on plant roots which will affect increase in girth growth.

3.4.3 Topography

The Sudd is generally very flat with clayish soils. The wetland has a mud sahelian region of Africa that slopes gently northwards. Soils are heterogeneous ranging from loamy, alkaline to very low organic matter content. The soil of seasonal flooding have organic matter content above 5% are more fertile, low salinity and are suitable for cultivation. Soils of permanent swamps are ectomorphic in origin, are acidic and the organic matter content vary from 5-45%3

3.4.4 Climate

Rainfall is around 800 to 900 mm/yr, occurring from April to November. Daytime temperature is on average 30-33°C during the dry season, dropping to an average of 26 to 28°C in the rainy season (Mohamed et al., 2004). The relative humidity exceeds 80% during the rainy season, and drops to below 50% in the dry season (mean of Juba, Wau and Malakal). High winds prevail during the wet season.

3.4.5 Wildlife and Mammals

Migratory mammals depend on the Sudd wetland for their dry season grazing. The Sudd is home to rare, endangered, vulnerable and threatened animal species. The hydrological regime of the Sudd influences the seasonal occurrence of the wildlife of the area. Populations of larger mammals also congregate in the Sudd area, which leads to some competition for water and grazing. They are hunted and are an important food source.

3.4.6 Birds

The Sudd is an important site for resident and migratory birds numbering over 400 species (Figure 3.4). The swamps, flood plains and grasslands support a rich animal diversity including hundreds of thousands of migratory birds. Some bird species are vulnerable while others are endangered. A rich variety of foods, grass seeds, crustacean, mollusks and aquatic insects are available to the birds as they migrate through the Sudd. It is a wintering ground for birds of international and regional conservation importance, such as the great white pelican, the black crowned crane, the white stork, and the black tern. The wetland is inhabited by the vulnerable Mongalla gazelle, the African elephant and the shoebill stork. Endemic fish, bird, mammal and plant species abound. The Sudd swamps hold by far the largest population of *Balaeniceps rex*. Aerial surveys in 1979-1982 counted a peak of 6,407 individuals. The site is probably also important for *Aythya nyroca* and, on passage, for *Falco naumanni*. In addition to those listed below, three species characteristic of the Sahel biome (A03) and five of the Somali-Masai biome (A08) have also been recorded. (see Table 3.2 below).

Table 3.2: Species resources in Sudd Marshes

Species	Season	Year	Min	Max	Quality	Criteria
Fulvous Whistling-duck (*Dendrocygna bicolor*)	winter	-	8775	8775	-	A4i
White-faced Whistling-duck (*Dendrocygna viduata*)	winter	-	51810	51810	-	A4i

Spur-winged Goose (*Plectropterus gambensis*)	winter	-	150216	150216	-	A4i
Comb Duck (*Sarkidiornis melanotos*)	winter	-	9611	9611	-	A4i
Yellow-billed Stork (*Mycteria ibis*)	winter	-	11154	11154	-	A4i
African Openbill (*Anastomus lamelligerus*)	winter	-	344487	344487	-	A4i
Woolly-necked Stork (*Ciconia episcopus*)	winter	-	2475	2475	-	A4i
White Stork (*Ciconia ciconia*)	winter	-	16500	16500	-	A4i
Saddle-billed Stork (*Ephippiorhynchus senegalensis*)	winter	-	4158	4158	-	A4i
Marabou Stork (*Leptoptilos crumeniferus*)	winter	-	359719	359719	-	A4i
African Sacred Ibis (*Threskiornis aethiopicus*)	winter	-	17688	17688	-	A4i
Glossy Ibis (*Plegadis falcinellus*)	winter	-	1695240	1695240	-	A4i
Squacco Heron (*Ardeola ralloides*)	winter	-	18414	18414	-	A4i
Cattle Egret (*Bubulcus ibis*)	winter	-	172359	172359	-	A4i
Goliath Heron (*Ardea goliath*)	winter	-	3819	3819	-	A4i
Purple Heron (*Ardea purpurea*)	winter	-	5049	5049	-	A4i
Great Egret (*Casmerodius albus*)	winter	-	19074	19074	-	A4i
Shoebill (*Balaeniceps rex*)	resident	-	0	0	-	A1
Shoebill (*Balaeniceps rex*)	winter	-	6407	6407	-	A1, A4i
Great White Pelican (*Pelecanus onocrotalus*)	winter	-	5643	5643	-	A4i
Pink-backed Pelican (*Pelecanus rufescens*)	winter	-	11187	11187	-	A4i
Reed Cormorant (*Phalacrocorax africanus*)	winter	-	8883	8883	-	A4i
Fox Kestrel (*Falco alopex*)	resident	1999	0	0	-	A3
Black Crowned-crane (*Balearica pavonina*)	winter	-	36823	36823	-	A1, A4i
Red-throated Bee-eater (*Merops bulocki*)	resident	1999	0	0	-	A3
Black-breasted Barbet (*Lybius rolleti*)	resident	1999	0	0	-	A3
Yellow-billed Shrike (*Corvinella corvina*)	resident	1999	0	0	-	A3
Emin's Shrike (*Lanius gubernator*)	resident	1999	0	0	-	A3
Piapiac (*Ptilostomus afer*)	resident	1999	0	0	-	A3

Sun Lark (*Galerida modesta*)	resident	1999	0	0	-	A3
Red-pate Cisticola (*Cisticola ruficeps*)	resident	1999	0	0	-	A3
Foxy Cisticola (*Cisticola troglodytes*)	resident	1999	0	0	-	A3
Red-winged Grey Warbler (*Drymocichla incana*)	resident	1999	0	0	-	A3
Purple Glossy-starling (*Lamprotornis purpureus*)	resident	1999	0	0	-	A3
Bronze-tailed Glossy-starling (*Lamprotornis chalcurus*)	resident	1999	0	0	-	A3
White-fronted Black-chat (*Myrmecocichla albifrons*)	resident	1999	0	0	-	A3
Chestnut-crowned Sparrow-weaver (*Plocepasser superciliosus*)	resident	1999	0	0	-	A3
Bush Petronia (*Petronia dentata*)	resident	1999	0	0	-	A3
Cinnamon Weaver (*Ploceus badius*)	resident	1999	0	0	-	A3
Red-winged Pytilia (*Pytilia phoenicoptera*)	resident	1999	0	0	-	A3
Black-bellied Firefinch (*Lagonosticta rara*)	resident	1999	0	0	-	A3
Black-rumped Waxbill (*Estrilda troglodytes*)	resident	1999	0	0	-	A3
A4iii (*Species group – waterbirds*)	winter	-	0	0	unknown	A4iii

Fig.3.4: Habitat for migratory birds in the Sudd marshes

3.4.7 Livestock production

Up to 1 million livestock (cattle, sheep and goats) are kept within the Sudd area. During the dry season, cattle-camps are set up on the banks of the main channels. Livestock (Figure 3.5) have accumulated during the war and their return to the Sudd area will result in deforestration and overgrazing.

Fig.3.5: Livestock resources in the Sudd Marshes

3.4.8 Fishing

In the central and southern parts of the swamps there are small and widely scattered fishing communities, some on small areas of dry land within the permanent swamp, but most of the population is concentrated on the comparatively small areas of relatively high ground. There is now commercial fishing (Figure 3.6) in addition to the traditional practice of only for subsistence. Access to fishing seems to be a free for all situations. Seasonal fishing continued to be an integral part of the subsistence economy of the region. A few species of fish (e.g. Clarias) were caught in large quantities with spears on the floodplain during dry down, and a wider variety of fish (e.g. Distichodus, Citharinus, Heterotis, Lates, Gymnarchus, tilapias and large mormyrids, catfishes and characids) with nets and hooks in the channels, lakes and vegetation of the perennial wetland. Year-round fishing had increased as a result of the loss of grazing by swamp encroachment. Canoe estimates ranged between 4000 and 7500, and daily landings of 17–28kg per canoe were recorded in the southern Sudd. Fish were consumed fresh or sun-dried. Commercial production was estimated at 700t and 68t respectively of processed sun-dried and salted, sun-dried fish in 1982. Fishery resources were underexploited but an expansion of the commercial sector was constrained by a scarcity of bulk collection, transportation and storage facilities, and a lack of commitment by fishermen.

3.4.9 Tourism

The Sudd wetland is an attractive wilderness for development in the tourism industry. However, construction of lodges, viewing and transport activities that come along with tourism increase stress levels on wildlife and environment. There is risk of pollution from uncontrolled solid and liquid waste disposal.

3.4.10 Hunting

Increased use of automatic weapons and vehicles has led to a decline in wildlife populations through uncontrolled hunting, poaching and greater accessibility to game.

3.4.11 Oil production

South Sudan now produces about 300000 b/d of high gravity, low sulphur crude. Block 5 B is at the center of the permanent Sudd swamp. Road construction and survey excavations during exploration for oil impact negatively on the environment. There are potential risks of air, water, and soil pollution for plants, wildlife, birds, livestock and humans who domiciled in the Sudd. Water contains toxic and cancerous chemicals.

Fig.3.6: Finishing activity in Sudd area

3.5 Development and management opportunities

From the previous section about natural resources, it can be concluded that the ecology of the Sudd wetland is composed of various ecosystems, grading from open water and submerged vegetation, to floating fringe vegetation, seasonally inundated woodland, rain-fed and river-fed grasslands, and floodplain scrubland. It is a wintering ground for birds of international and regional conservation importance such as Pelecanus onocrotalus, Balearica pavonina, Ciconia ciconia and Chlidonias nigra; and is home to some endemic fish, birds, mammalian and plant species, and to the vulnerable Mongalla gazelle, African elephant and shoebill stork. Migratory mammals depend on the wetland for their dry season grazing. Hydrologically the Sudd wetland is regarded as a giant filter that controls and normalizes water quality and a giant sponge that stabilizes water flow. It is the major source of water for domestic, livestock, and wildlife use, and an important source of fish. The occupants living within and adjacent to the Sudd region are almost exclusively Dinka, Nuer and Shilluk. The socio-economic and cultural activities of these Nilotes are entirely dependent on the Sudd wetland and on its annual floods and rains to regenerate floodplain grasses to feed their cattle. They move from their permanent settlements on the highlands to dry season grazing in the intermediate lands (toich) at the beginning of the dry season and return to the highlands in May-June when the rainy season starts. Oil exploration as Sudd contains Sudan's largest oil block has direct impact on the environment. There are potential risks of air, water, and soil pollution for plants, wildlife, birds, livestock and human being. This may result that the produced water contains toxic and cancerous chemical. Jonglei Canal Project, which is currently on hold, but would reduce wet and dry season flows by 20 and 10% respectively, thus impacting the wetland's ecology and consequently its inhabitants. There are three protected areas within the Sudd, but no special protection measures or management plan is in place. Therefore, the following potential can be defined for management and developments:

- Human livelihood
- Land use management
- Vegetation resource management
- Livestock management (production and marketing)
- Species management
- Fisheries and aquacultures
- Flood and draught threats management
- Waste management
- Wildlife management
- Oil and water resource management
- Hunting legalization
- Tourism improvement and management
- Hunting legalization
- Water resource reservation
- Settlement management
- Impact of Jonglei Canal project on water resources and ecosystem

3.6 Development principles

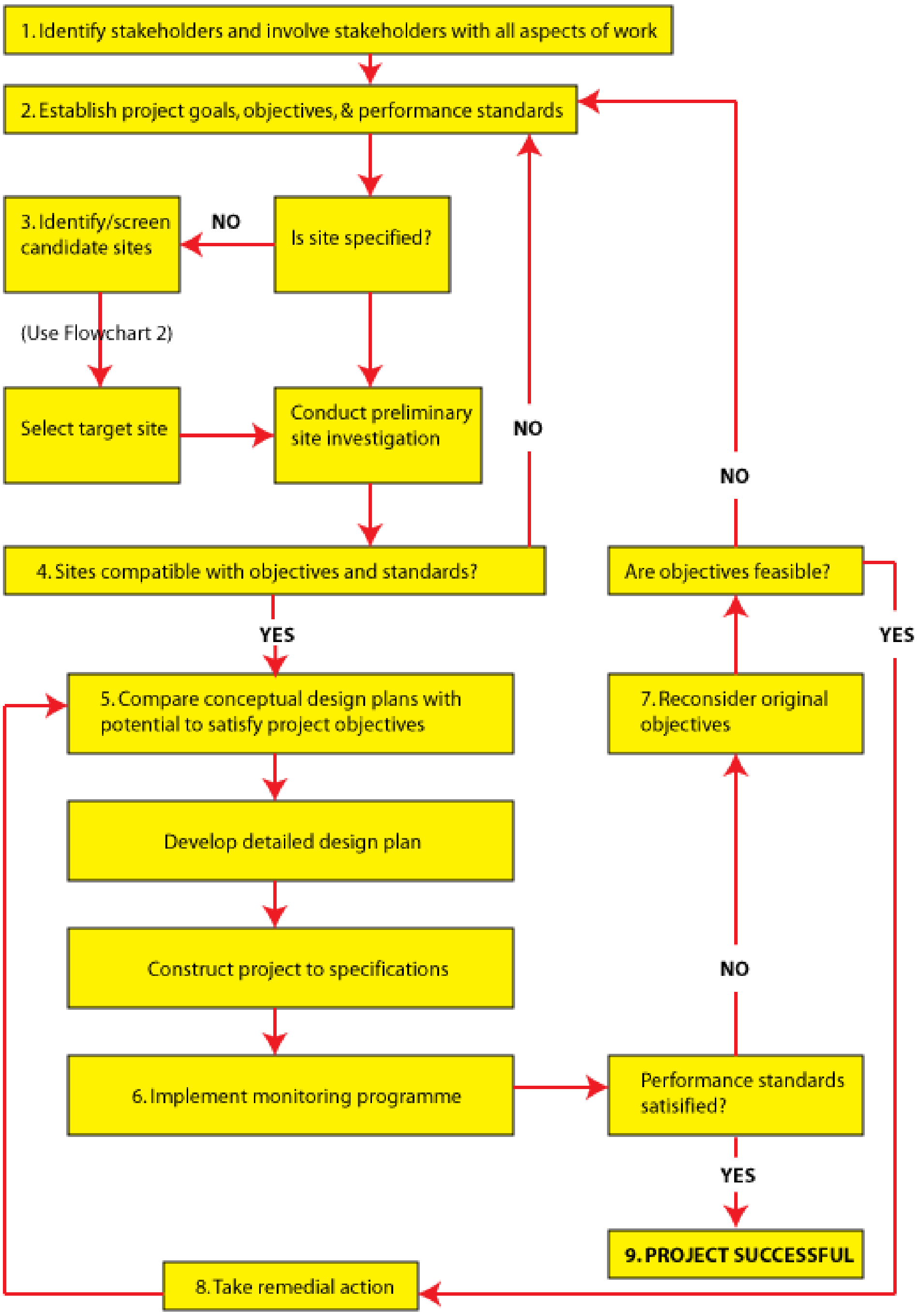
3.6.1 Ramsar Convention

The Convention on Wetlands, signed in Ramsar, Iran, in 1971, is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 158 Contracting Parties to the Convention, with 1752 wetland sites, totaling 161 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance. In ceremonies in Khartoum on 5 June 2006, World Environment Day, Sudan's Minister of Environment and Physical Development, **Dr. Ahmed Babikar Nehar**, announced the designation of the Sudd marshes as his country's second Wetland of International Importance, along with the Dinder National Park Ramsar site and UNESCO Biosphere Reserve. Ramsar Convention's Mission Statement is:

“Conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world"

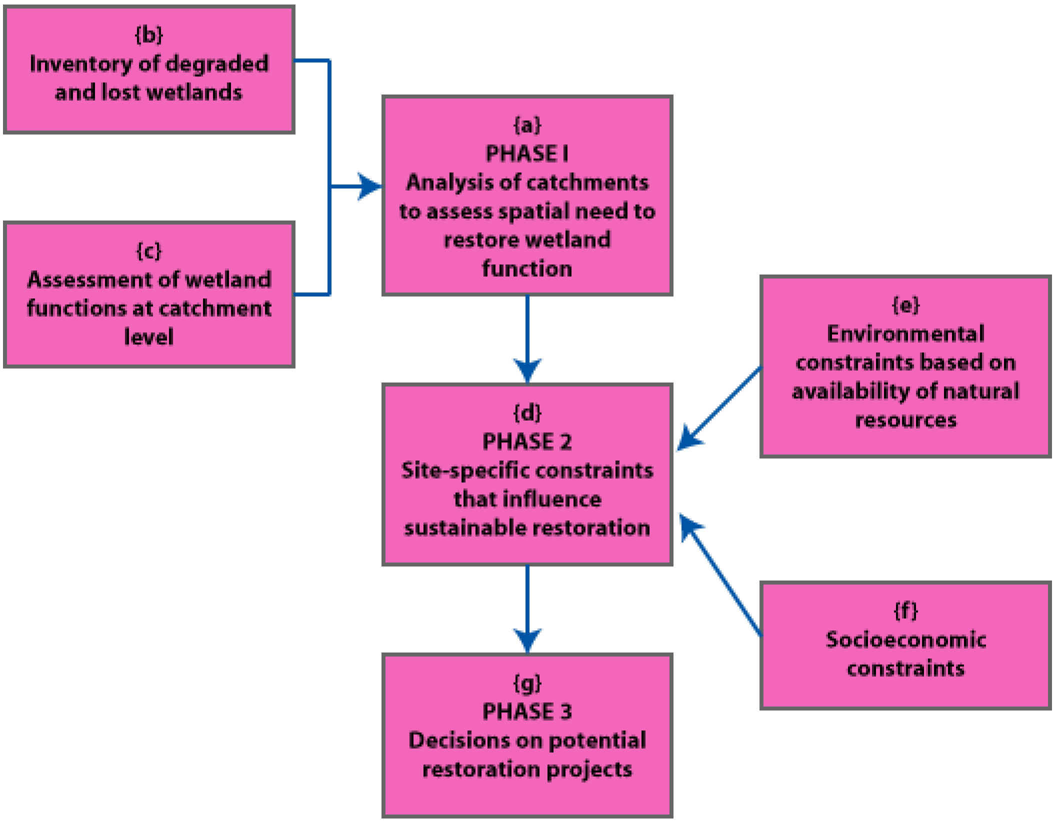
The Ramsar convection sets step by step process to guideline the identification, development, and implementation of a restoration project. These principles can be summarized as follows (Flow Charts 1 and 2):

1. Wetland restoration priorities should be established basing on national inventory
2. Goals, objectives, and performance should be clearly understood
3. Careful planning will limit the possibility of undesirable side effects
4. Natural process and existing conditions should be taken into consideration during project preparation
5. Maintenance and conservation of existing wetlands is always preferable and more economical than their subsequent restoration
6. The linkage between upland and wetland habitats should not be ignored
7. The minimum acceptable scale for wetland restoration planning should be at the catchment level



Numbers correspond to numbers in parentheses in the text

Flowchart 1: Guidelines for wetland restoration



Flowchart 2: Process for identification of potential wetland restoration projects
(Letters { } correspond to explanations in the text)

8- Water allocation principles should be considered
9- Restoration should be an open process involving all types and distant stakeholders
10- A framework for wetland monitoring program suitable for long term stewardship
11- Traditional resource management and local people experience should be incorporated
12- Adaptable management should be applied in the light of evaluating the project against its goal, objectives and performance standards.
13- Information dissemination on planning proposal, successes can result in continuous involvement of stakeholders and programs
14- Intervention should be coupled with measures to raise awareness to improve behaviors and practices.

Chapter 4. Sudd Boundary Delineation Using Remote Sensing

4.1 Sources of Satellite Images

A number of sites are used to download images to delineate the Sudd boundries. Some of these sites are listed below:

1- SPOT Vegetation NDVI

SPOT Vegetation

More information:
http://www.spot-vegetation.com

Data download:
http://free.vgt.vito.be/

Data availability:
Freely available 3 months after insertion in the
getation archive. Registration required.

Resolution:
Spatial -> 1-km
Temporal -> 10-day global syntheses

Swath width:
Global syntheses

Image information:
Real NDVI = 0.004 * DN – 0.1
Example fig 4.1

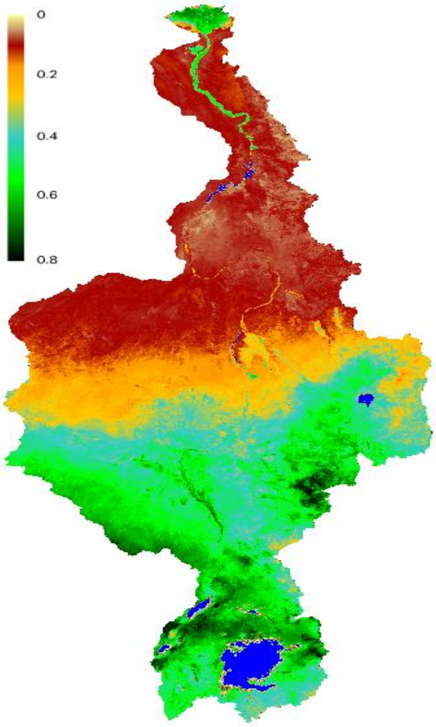
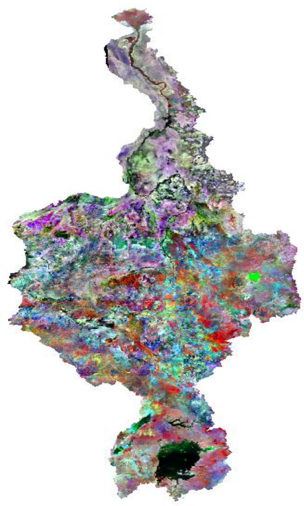


Fig.4.1: NDVI for the period 1-15 January 2003

2- Landsat GeoCover Mosaics

The GeoCover mosaic is a global set of regional images mosaicked from the Landsat GeoCover data set. This project was designed at NASA Stennis Space Center (https://zulu.ssc.nasa.gov/mrsid/). It is also called GeoCover circa 1990 (based on Landsat 5-TM) and circa 2000 (based on Landsat 7-ETM).



More information:
http://glcf.umiacs.umd.edu/data/mosaic/

Data download:
http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp

Data availability:
Datasets are created with images from circa 1990 and 2000. Use is free to all. The US Government holds the ultimate ownership.

Resolution:
Spatial -> 14.25 meter.

Swath width:
Available for the entire earth land surface

Image information:
UTM
MrSid format
Example fig 4.2.

Fig.4.2: Landsat 7ETM GeoCover mosaic

3- Africa Land Cover Characteristics Data Base

The Africa land cover data base is one portion of a global land cover characteristics data base that is being developed on a continent-by-continent basis. The data base is based on 1-km AVHRR data spanning April 1992 through March 1993. Each data base has unique elements and a core set of derived thematic maps produced through the aggregation of seasonal land cover regions. The core set consists of: Global Ecosystems, IGBP Land Cover Classification, US Geological Survey Land Use/Cover System, Simple Biosphere (2) Model and the Biosphere-Atmosphere Transfer Scheme.

More information:
http://edcsns17.cr.usgs.gov/glcc/glcc_version1.html#Africa
http://edcsns17.cr.usgs.gov/glcc/afdoc1_2.html

Data download:
ftp://edcftp.cr.usgs.gov/pub/data/glcc/af/lambert/

Data availability:
April 1992 – March 1993

Resolution:
Spatial -> 1-km
Temporal -> monthly NDVI Composite Images are available for the period April 1992 - March 1993
Swath width:
Products at continental scale
Example is Figure 4.3
Image information:
Flat, headerless raster format
Pixel values correspond to class numbers defined in classification scheme legends
Single-band images
Available in either Interrupted Goode Homolosine or Lamber Azimuthal Equal Area projections.

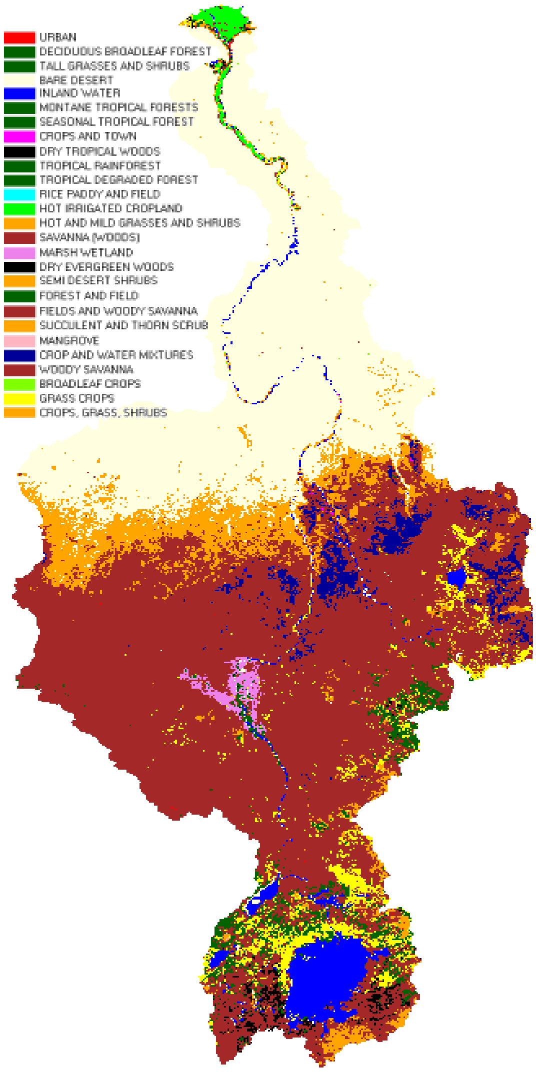


Fig.4.3: Global Ecosystems

4.2 Data processing

Different potential methods are used for image interpretation and wetland delineation. Landsat images have been selected for wetland mapping. Despite the fact of having several wetland classifications and definitions the primary element of the wetland is that it has remarkable water content/cover. Water as a land cover class has to be detected from the satellite image and verified using ground truthing. The water detection will be applied using vegetation index technique and the ground truthing will be obtained from supervised land cover classification of the satellite image. Available information about the ground such as maps, photographs and local personnel can be used to develop the supervised classification. Better results are obtained if field trips are used for ground truthing.

4.2.1 Vegetation Index

A vegetative index is a value that is calculated (or derived) from sets of remotely-sensed data that is used to quantify the vegetative cover on the Earth's surface. Though many vegetative indices exist, the most widely used index is the Normalized Difference Vegetative Index (**NDVI**). The NDVI, like most other vegetative indices, is calculated as a ratio between measured reflectivity in the red and near infrared portions of the electromagnetic spectrum. These two spectral bands are chosen because they are most affected by the absorption of chlorophyll in leafy green vegetation and by the density of green vegetation on the surface. Also, in red and near-infrared bands, the contrast between vegetation and soil is at a maximum.

The NDVI is a type of product known as a transformation, which is created by transforming raw image data into an entirely new image using mathematical formulas (or algorithms) to calculate the colour value of each pixel. This type of product is especially useful in multi-spectral remote sensing since transformations can be created that highlight relationships and differences in spectral intensity across multiple bands of the electromagnetic spectrum. The NDVI transformation is computed as the ratio of the measured intensities in the red (R) and near infrared (NIR) spectral bands using the following formula:

NDVI = (NIR - red) / (NIR + red)

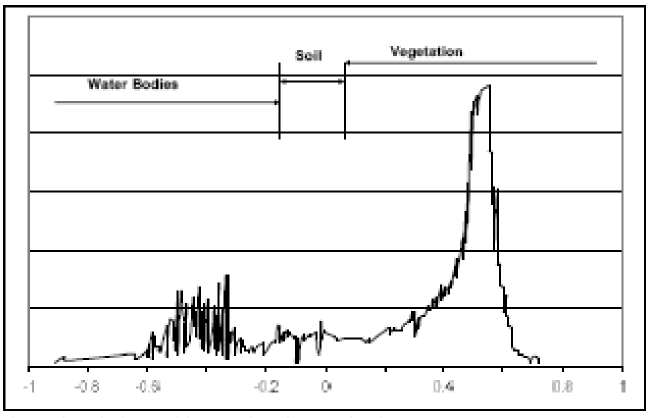


Fig.4.4: Typical NDVI histogram distribution for LandSat image

The resulting index value is sensitive to the presence of vegetation on the Earth's land surface and can be used to address issues of water extent, vegetation type, amount, and condition (Figure 4.4). The Thematic Mapper (TM and Enhanced Thematic Mapper Plus (ETM+) bands 3 and 4) provide R and NIR measurements and therefore can be used to generate NDVI data sets with the following formula:

$$\text{(ETM+) NDVI} = (\text{Band } 4 - \text{Band } 3) / (\text{Band } 4 + \text{Band } 3)$$

4.2.2 Classification

An important part of image analysis is identifying groups of pixels that have similar spectral characteristics and to determine the various features or land cover classes represented by these groups. This form of analysis is known as classification. Visual classification relies on the analyst's ability to use visual elements (tone, contrast, shape, etc) to classify an image. Digital image classification is based on the spectral information used to create the image and classifies each individual pixel based on its spectral characteristics. The result of a classification is that all pixels in an image are assigned to particular classes or themes (e.g. water, vegetation, forest, specific crop, etc.), resulting in a classified image that is essentially a thematic map of the original image. The theme of the classification is selectable, thus a classification can be performed to observe land use patterns, geology, vegetation types, or rainfall. One band classification is usually very difficult to classify since more than one surface type will exhibit the same digital number. Thus, any spectral classes in a single band classification will likely contain several information classes, and distinguishing between them would be difficult. Normally two or more bands are used for classification, and their combined digital numbers are used to identify the spectral signatures of the spectral classes present in the image. The more bands used to create a classification, the more likely the analyst will get a set of unique land cover classes. Unsupervised classification is essentially the opposite of supervised classification.

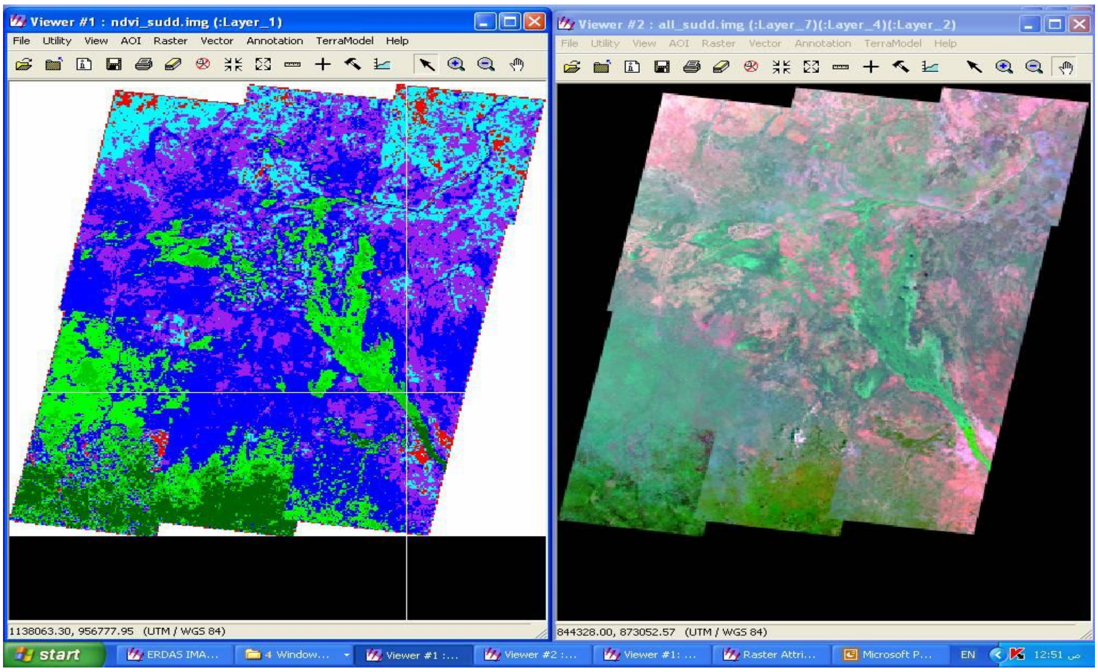


Fig.4.5: Landsat tiles covered the Sudd area

The pixels in an image are examined by the computer and classified into spectral classes. The grouping is based solely on the numerical information in the data and the spectral classes are later matched by the analyst to information classes. In order to create an unsupervised classification the analyst typically determines the number of spectral classes to identify and a computer algorithm will find pixels with similar spectral properties and group them accordingly. The Sudd area is covered by about 10 Landsat tiles, Figures 4.5 and 4.6 with spatial resolution 30 meters.

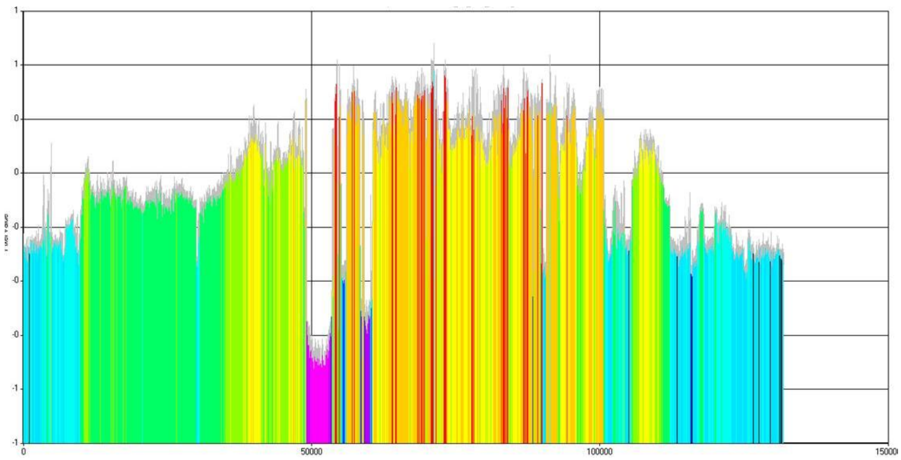


Fig.4.6: Cross section infrared from Spot NDVI image, at the Sudd area

4.2.3 Results and analysis

A sample is used to test the decided procedure however, it is concluded that compiling the entire image before generating the NDVI is resulting in some error due to the differences in the atmospheric conditions when each image was captured. Therefore it is decided to work with images one by one and apply radiometric correction (haze reduction) to all images (separately) before generating the NDVI. This procedure will add value to accelerating the generation process on the computer because compiling the Sudd entire images is resulting in huge file. Then outputs (Figures 4.7 and 4.8) (water and wetland classes) will be collected. Although the vegetation index can be used to extract the water it was found that NDVI is the best for separating water from other classes.

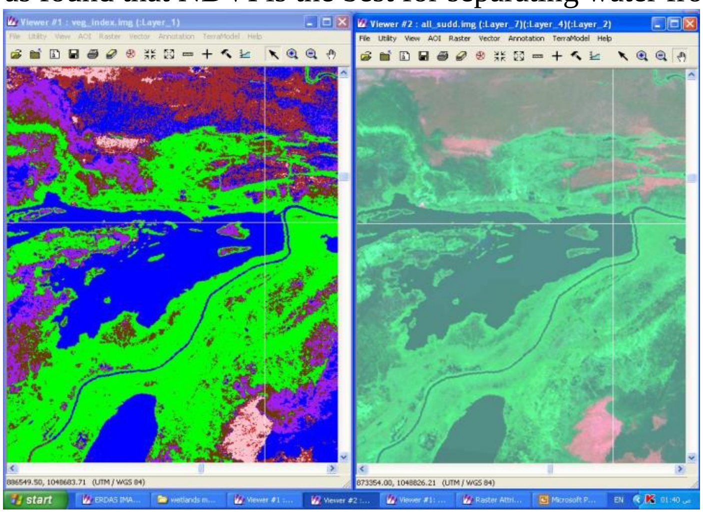


Fig.4.7: Classes for water and vegetations for different location at the study area

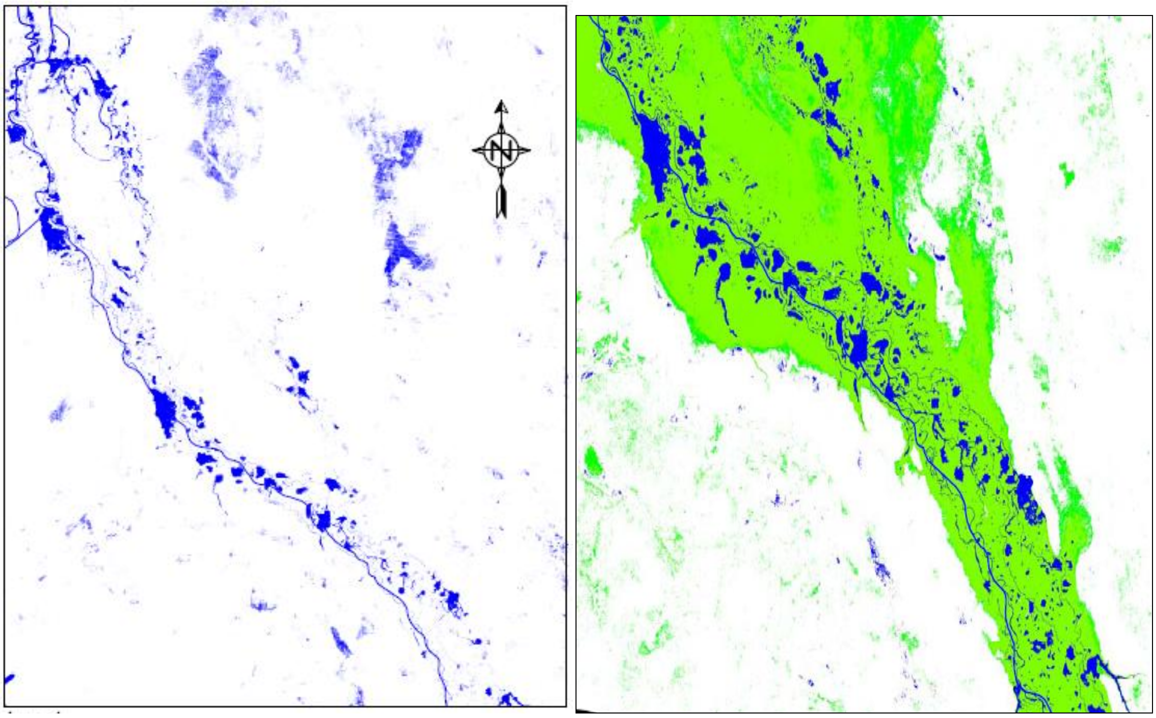


Fig.4.8: The boundary of Sudd Marshes

4.3 Sudd boundary delineation

The Sudd is a large swamp area formed by the White Nile in southern Sudan. The spatial extent of the swamp changes in the wet and the dry seasons. The river flows through multiple tangled channels in a pattern that changes each year. Sometimes vegetation builds up into an island, but these eventually break up. The remote sensing data will be used to define the spatial extent of the Area and if possible to define the hydrological units inside. Reviewing the digital elevation model of the area (Figure 4.9) shows that the minimum elevation is 350m above mean see level and the maximum is about 3200m at the boundary of the Nile basin in this area. The elevations have been classified as in the map where the first class is between 350 and 400 and the second is between 400 and 450. Both classes are forming a wide basin from west to east and containing the whole Sudd area. From this result, the difference in the elevation did not help in defining the internal hydrological units. Therefore the river streams will be used to describe the internal units.

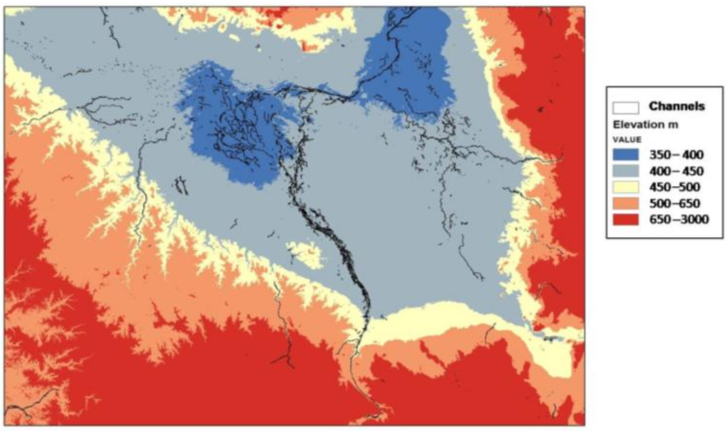


Fig.4.9: Sudd Digital Elevation Model

There are three main waterways through the swamp. The swamps can be divided into four large basins, of which Bahr-el-Jebel is the central basin. The other basins are Bahr-el-Ghazal to the west, Sobat river basin to the east and the Machar marshes to the north-east. Bahr-el-Jebel system consists of two main rivers, Bahr-el-Jebel, the main course of the White Nile, to the west and the smaller Bahr-el-Zeraf to the east. The area is extremely flat with an average slope of only 10 cm/km and the central part of the Sudd is about 600 km along the river course. The rainfall season is between April and September with an average temperature between 33ºC during the hot season, dropping to an average of 18ºC in the cold season.

4.3.1 Mapping the SUDD extent

Following the months of the dry and rainy seasons, the extent of the vegetation cover over the months can be delineated. Different years of high, medium, and low floods should be selected to map the vegetation in the dry and wet season of each year. However, the flow over the year is almost constant. Therefore, the dominant factor will be the rainfall over the year. The months of April and August have been selected to compare the vegetation cover and define the marshes' extent. Satellite images have been used to generate vegetation index.

4.3.2 Methodology

The Normalized Difference Vegetation Index (NDVI) has been used to distinguish between vegetation, water, and soil classes from satellite images. By applying the NDVI formula, the result will be in the range between -1 to +1 where the highest value means green or dense vegetation and the lower value means no vegetation. Many satellites have been designed to capture the reflectance in the NIR and the red band width. Landsat satellite images were collected as explained in section 4.1 to cover the Sudd area and the NDVI values were generated in spatial resolution (30m x 30m). The available free Landsat images do not cover the dry and wet seasons in two complete sets. It was possible to generate one NDVI file at the dry season but it was not possible to do it for the wet season. Other sources of information were investigated. Spot satellite was designed mainly to study the vegetation around the world. This satellite has the ability to generate NDVI for more frequent time but with lower spatial resolution (1km x 1km). 10-days NDVI files were collected and monthly NDVI were generated from the spot satellite images at resolution of 1km. 36 layer Spot images are used to extract the NDVI and thus the changes in water surface area throughout 1999. They contain raw data (DN values), and the NDVI values had to be computed from the DN values using the following formula:

$$\textbf{Real NDVI} = \mathbf{a * DN + b}$$

where:

a = 0.004 and b = -0.1

The computation of the real NDVI values is done using ERDAS imagine 9.2 the Model Maker, (see Figure 4.10) the output is float, and may contain negative values.

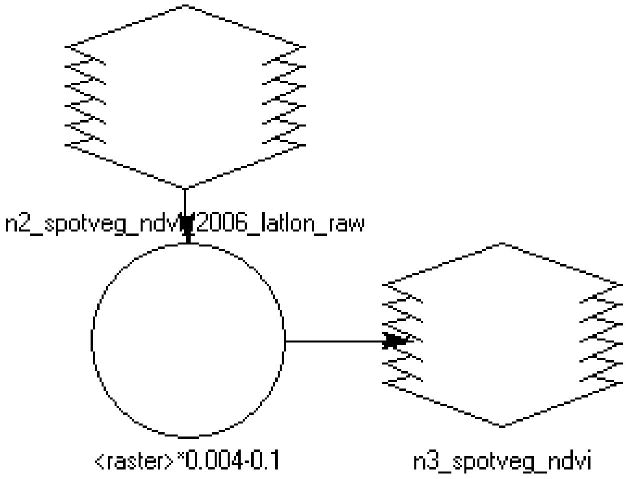


Fig.4.10: The Model Maker

4.3.3 Change Detection

The generated monthly NDVI for the year 1999 was studied and analyzed. Figure 4.11 shows the one of the monthly NDVI layers and the location of some cross sections for further analyses. Section x-x is located along the Nile River, section y-y is located across the river in the most flat area, and section z-z is going in different angle with the river. The values extracted from these sections represent the DN values corresponding to NDVI values at each month for the same points in the section. Figure 4.12 represents the values of NDVI at the section x-x. It appears that the month of April has the minimum values and the month of August has the highest values. Also the change in NDVI values can be seen along sections y-y and Z-Z as shown in Figures 4.13 and 4.14. Figure 4.15 indicates the trend of NDVI values along sec x-x in different seasons.

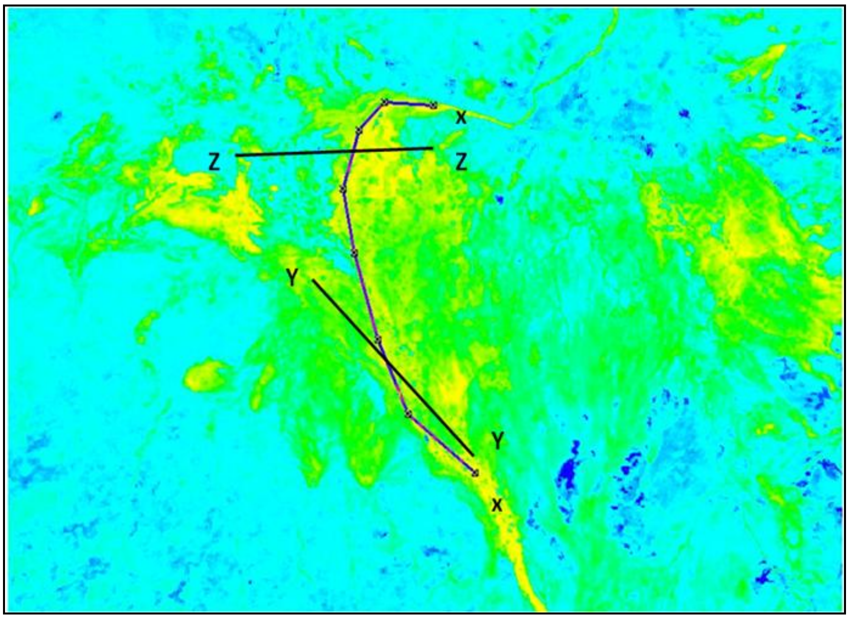


Fig.4.11: Monthly NDVI layer and cross section location

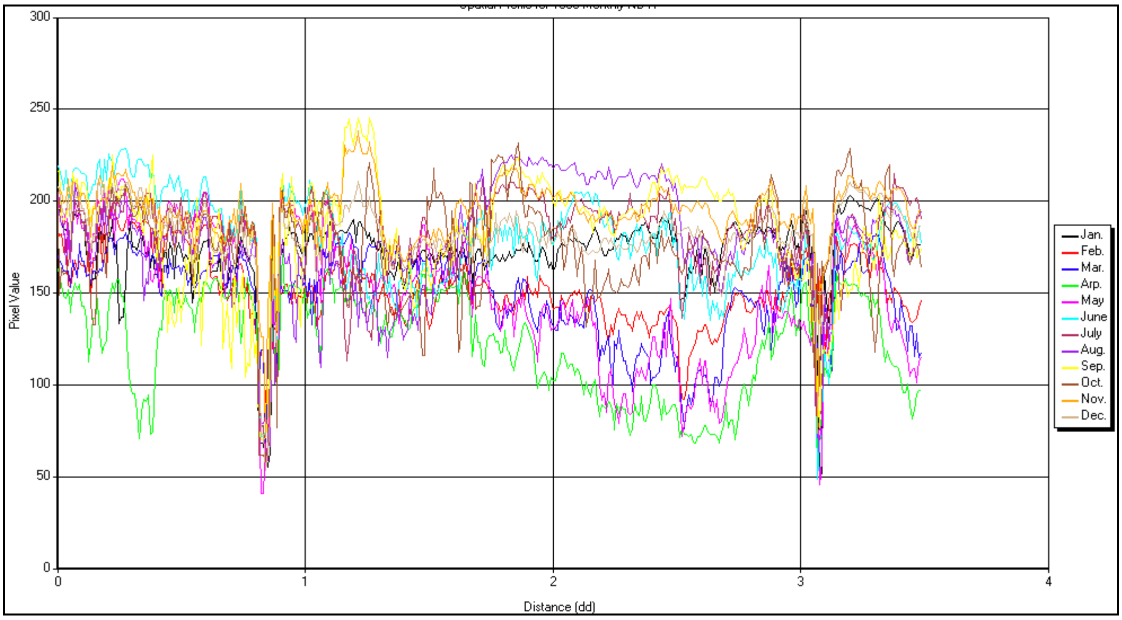


Fig.4.12: NDVI values at cross section x-x

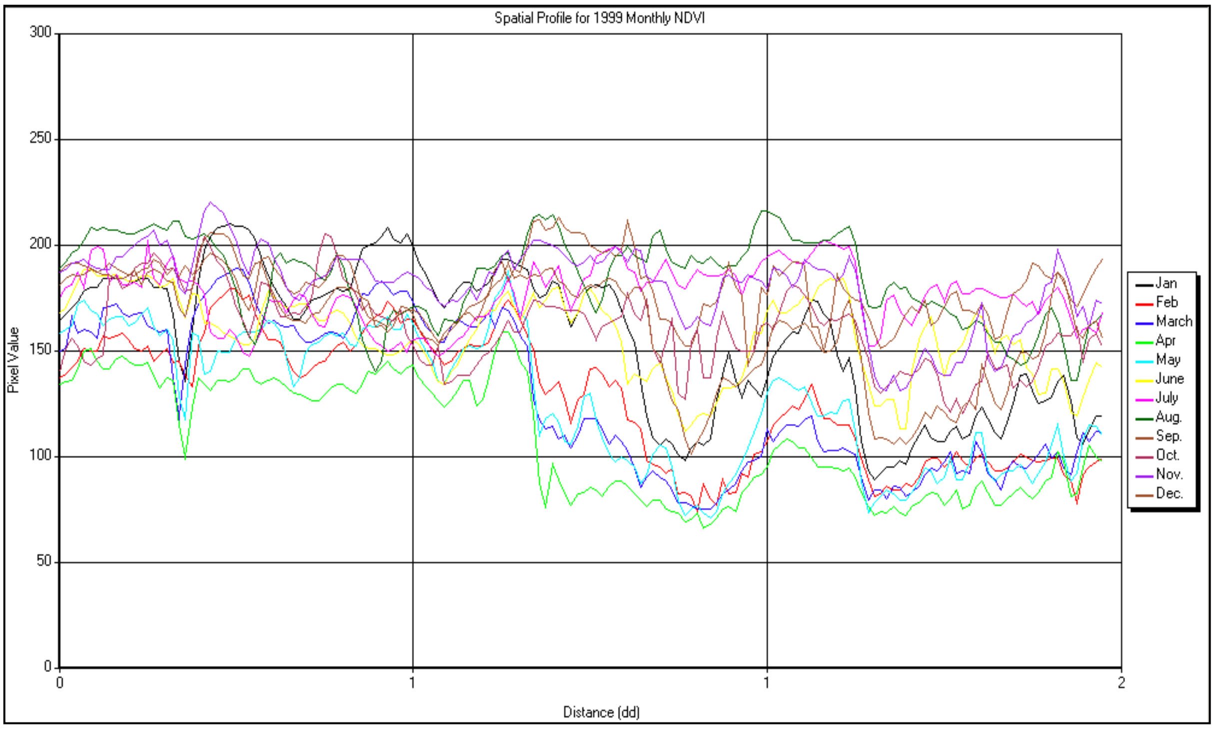


Fig.4.13: NDVI values along section y-y

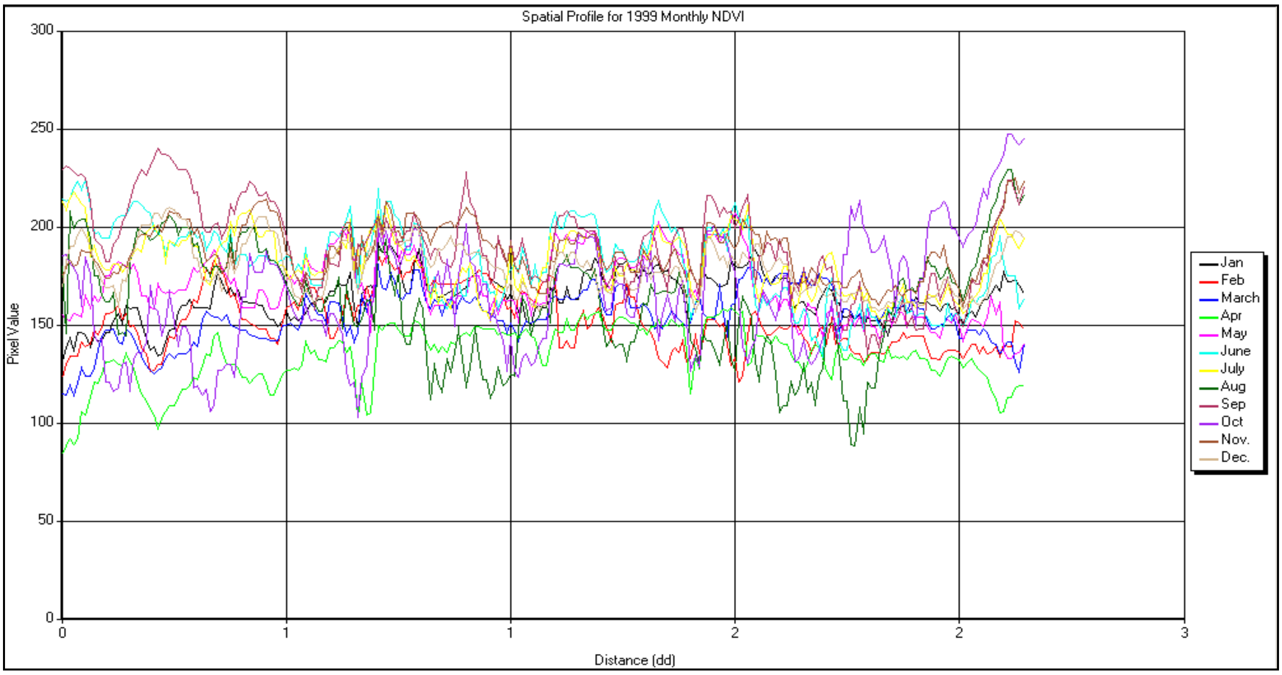


Fig.4.14: NDVI values along section z-z

Table 4.1 illustrates the values of the vegetation cover for ten days interval for the whole period (1999-2006)

Table 4.1: change in the green cover for Sudd area during 1999-2006

Period	Month	Area (Km^2)							
		99	2000	2001	2002	2003	2004	2005	2006
1st ten days	Jan	88509	79833	40458	44822	30916	49148	36678	48572
2^{sc} ten days		78259	66645	33220	42588	27183	42563	34769	42626
3rd ten days		75593	57742	34399	38300	23137	39992	33499	42011
1st ten days	Feb	57336	39122	24847	30838	22561	38725	26769	36687
2^{sc} ten days		54834	33430	18818	23988	20429	32567	26468	29485
3rd ten days		29609	37772	15087	23825	17569	32770	23716	29993
1st ten days	March	47789	28525	14629	23690	16867	23092	22527	20482
2^{sc} ten days		48750	30541	13772	13130	13218	25097	20184	23662
3rd ten days		40511	29785	17775	14340	13971	25001	23541	21919
1st ten days	April	36452	30240	17371	27655	17022	18335	14331	26004
2^{sc} ten days		39017	37815	24604	23019	13720	30292	17670	16244
3rd ten days		37312	53981	27194	21593	18231	31353	20302	22813
1st ten days	May	55198	54792	26569	26703	18729	39962	26209	26874
2^{sc} ten days		77664	63265	20305	23217	21797	33443	22551	63617
3rd ten days		92817	67504	46170	31496	26413	33492	39268	91349

Period	Month	Area (Km^2)							
		99	2000	2001	2002	2003	2004	2005	2006
1st ten days	June	100551	83530	60870	33598	50836	59834	46542	94200
2sc ten days		106401	94453	81094	48635	61516	72175	90701	96875
3rd ten days		108204	89933	89296	61644	88687	79011	95511	99934
1st ten days	July	118193	98430	95153	88147	95449	92405	104904	99931
2sc ten days		116572	112645	98686	97338	99435	101519	105347	104765
3rd ten days		119183	113865	92081	88194	104700	102144	105365	103812
1st ten days	August	118444	115200	104553	91973	104700	98301	105471	84041
2sc ten days		117669	112843	105368	100707	105155	100866	105403	103211
3rd ten days		119543	114199	101916	104836	104244	105328	105453	104972
1st ten days	Sep.	119284	115679	104199	105229	102689	105412	105304	105441
2sc ten days		119504	115772	105466	105377	105471	105393	105451	105483
3rd ten days		119434	115616	105423	105332	105451	105419	105458	103848
1st ten days	Oct.	117774	114978	105395	105264	105407	105461	105437	105463
2sc ten days		119212	115687	105263	104429	105215	105373	105218	105433
3rd ten days		119591	115658	104012	103855	104976	104647	103946	104746
1st ten days	Nov.	119516	110063	100111	96265	100440	98614	99209	104742
2sc ten days		119484	107013	95458	81131	93834	91175	89968	99461
3rd ten days		119115	82746	83033	61414	88150	66772	80064	94730
1st ten days	Dec.	116667	75302	73528	40727	76340	56924	62946	76956
2sc ten days		114262	57864	63021	35474	66929	48100	58767	63156
3rd ten days		97812	49553	54214	33099	53872	41006	49585	63415

The maximum green cover (Figure 4.16) is 119591 Km^2 and occurred in October 1999, while the minimum area is 13130 km^2 occurred in March 2002, the average area is estimated by 69346 km^2. As a result of the analysis of the previous charts it was decided to compare the months of April and August (Figures 4.17-4.19) to define the Sudd extent in the dry and wet season as a maximum and minimum extent.

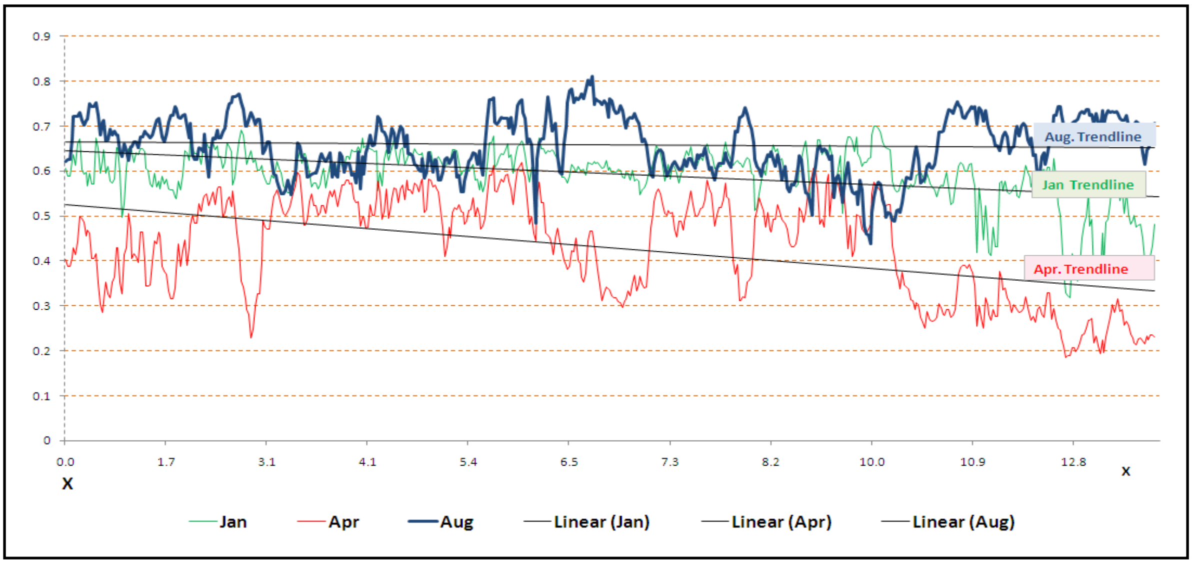


Fig.4.15: Trend of NDVI values along Sec X-X in different seasons

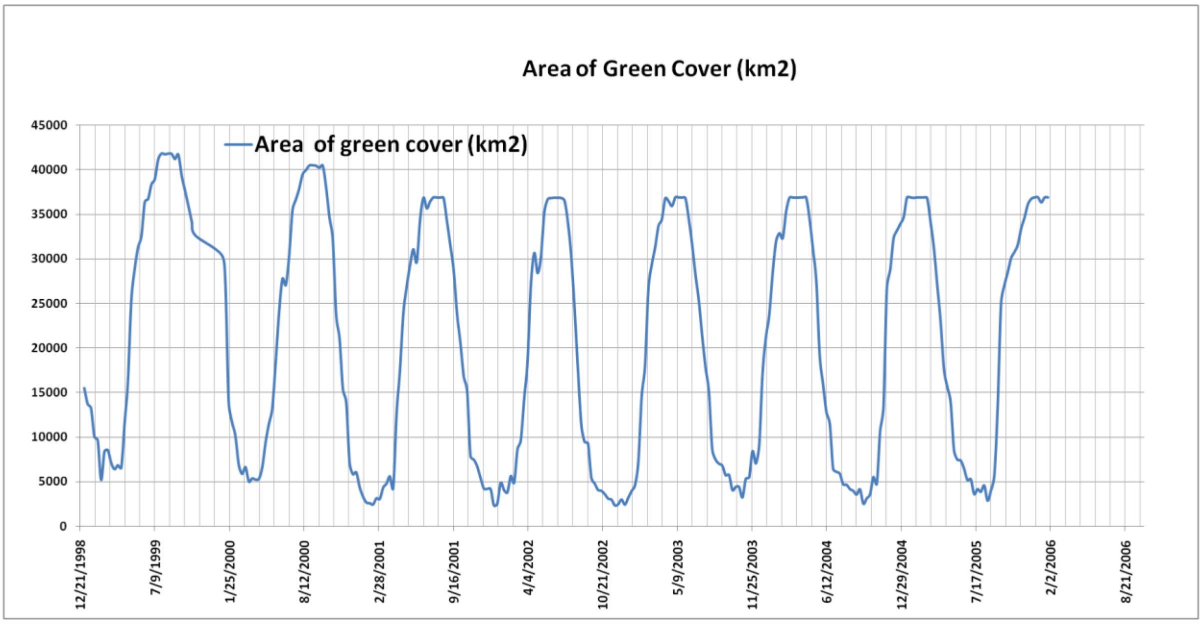


Fig.4.16: Change in the green cover for Sudd during 1999-2006

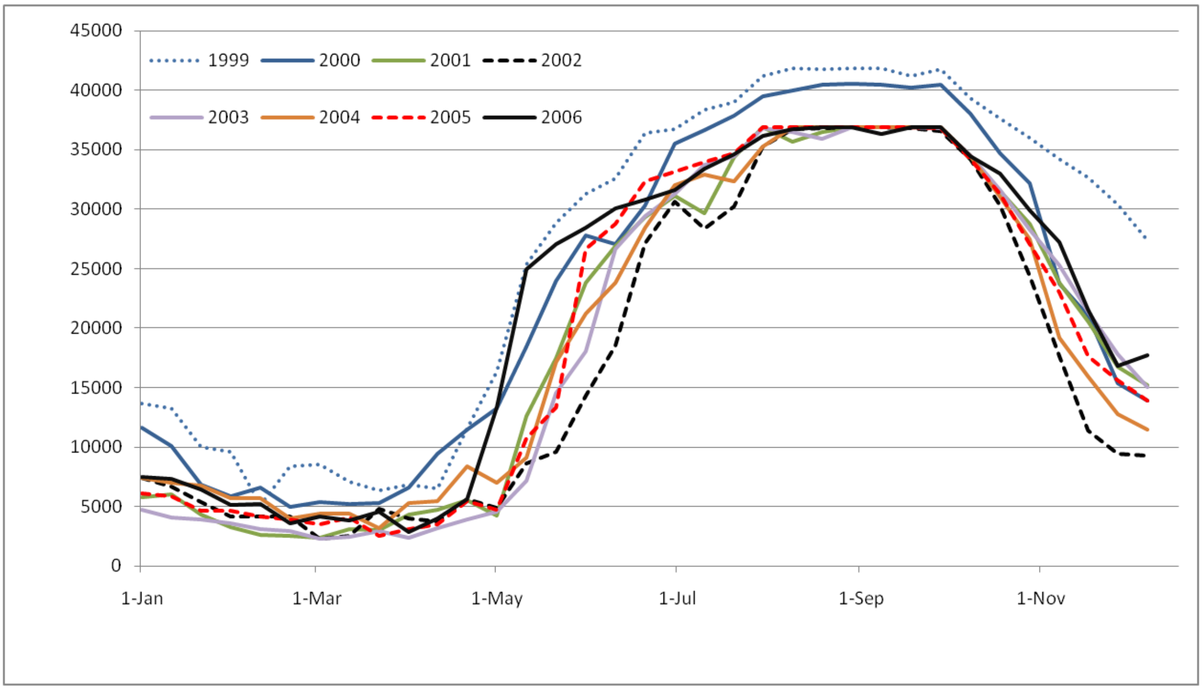


Fig.4.17: Comparison of change in green area during 1999-2006

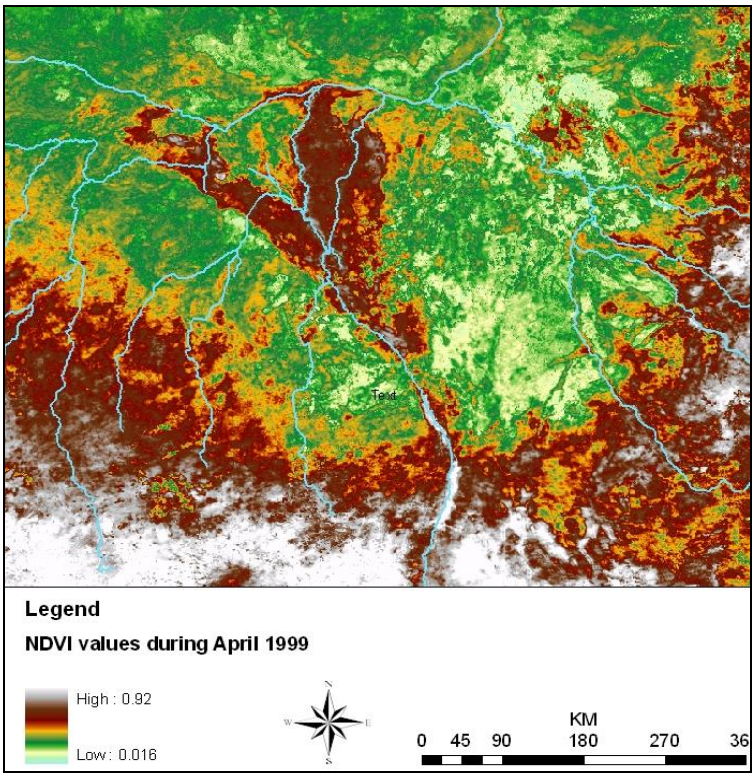


Fig.4.18: Spot NDVI for April, 1999

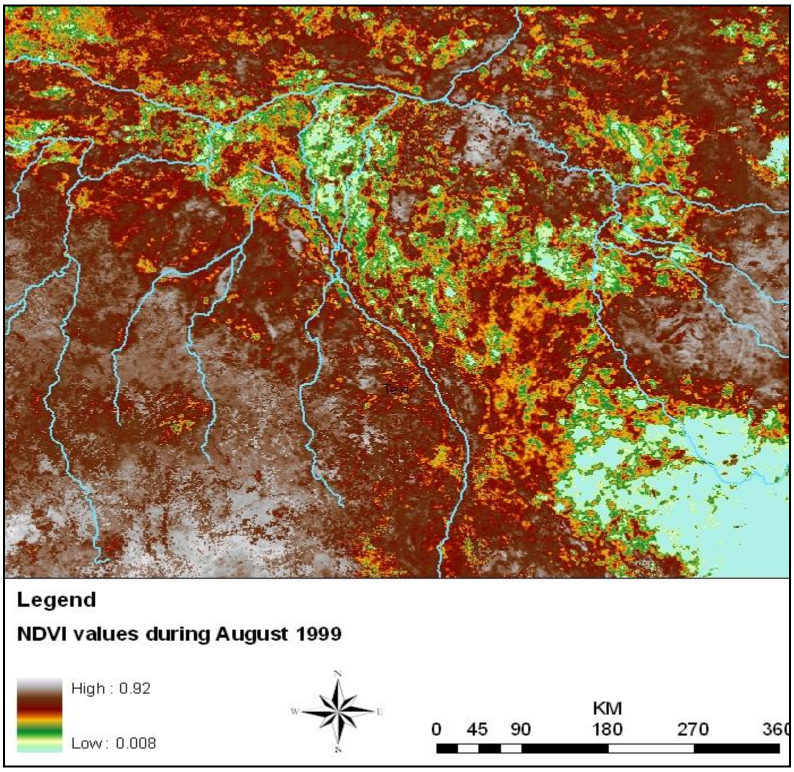


Fig.4.19: Spot NDVI for August, 1999

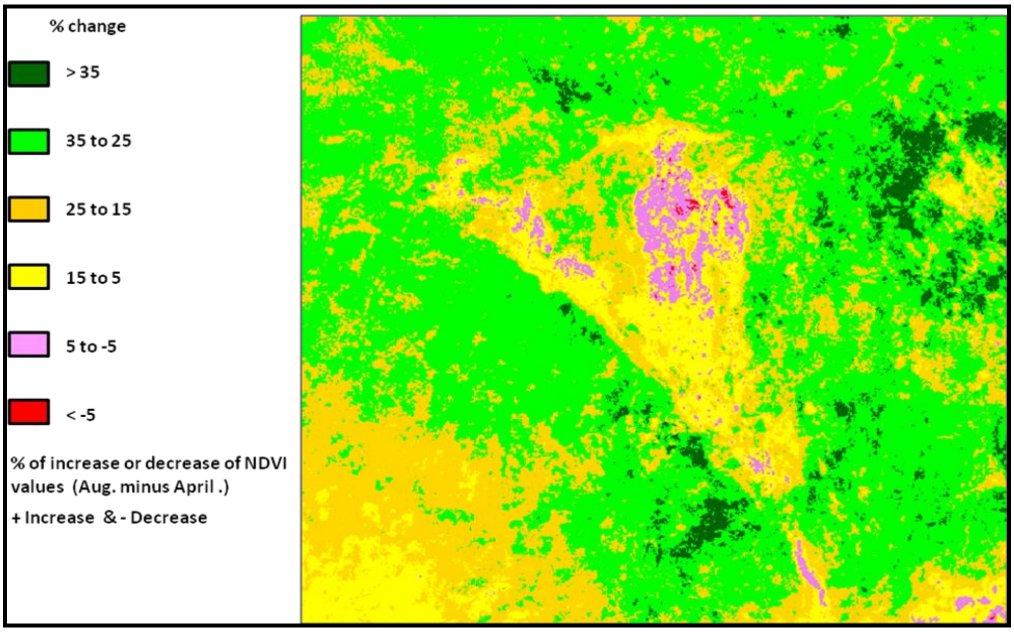


Fig.4.20: Change in vegetation index between April and August for spot 1999 time series image

Figure 4.20 shows the difference between NDVI values in April and August. A constant value was added to each pixel in order to avoid the miscalculation of the negative values.

Value = ((NDVI.August+2) – (NDVI.April+2))*100/(NDVI.April)

The classification of the output can be interpreted as indicated in table 4.2.

Table 4.2: Output Classifications

Class Number	% of changes	Interpretation
1	Greater than 35	Areas where the NDVI values increased in August by more than 35 %. It appears in the high lands around the Sudd region as a result of the heavy rainfall.
2	35 to 25	Less magnitude of increasing the vegetation cover. This increase is due to the normal rate of rainfall on the whole region.
3	25 to 15	Moderate change in the vegetation cover. This means that these areas has reasonably amount of moisture where the vegetation did not die completely during the dry season
4	15 to 5	This represents very small changes in the vegetation cover between April and August. These areas might be floating vegetation with considered amount of water or moisture all over the year.
5	5 to -5	Areas with no changes of the NDVI values. This means that it is the same conditions and most probably it contains rivers, lagoons, and floating vegetation. In general it means that these areas are wet during the whole year.
6	Less than -5	Areas were higher in vegetation in April more than in August. This means that it contains floating vegetation and it had been moved from the original location or islands which had been burned.

4.4 Conclusion

The outline of class number 3 is the maximum outline of the swamp area this outline should contain classes number 4, 5, and 6. Some areas classified as class 3 and 4 and located to the west-south direction should not be considered within the Sudd area. This area is disconnected from the central part of the Sudd where the mountainous area is separating them.

As the maximum boundaries if the Sudd will be the outline of class number 3, the minimum boundaries will be the outline of class number 4. The minimum and maximum buffers that surrounding the extents of the Sudd area were estimated for both dry and wet seasons as 17,000 and 45,632 km^2 respectively. The study recommends that using additional sources of aqua-satellite images to define the actual extent of the permanent and seasonal wetland to minimize the error from vegetation mixed with water.

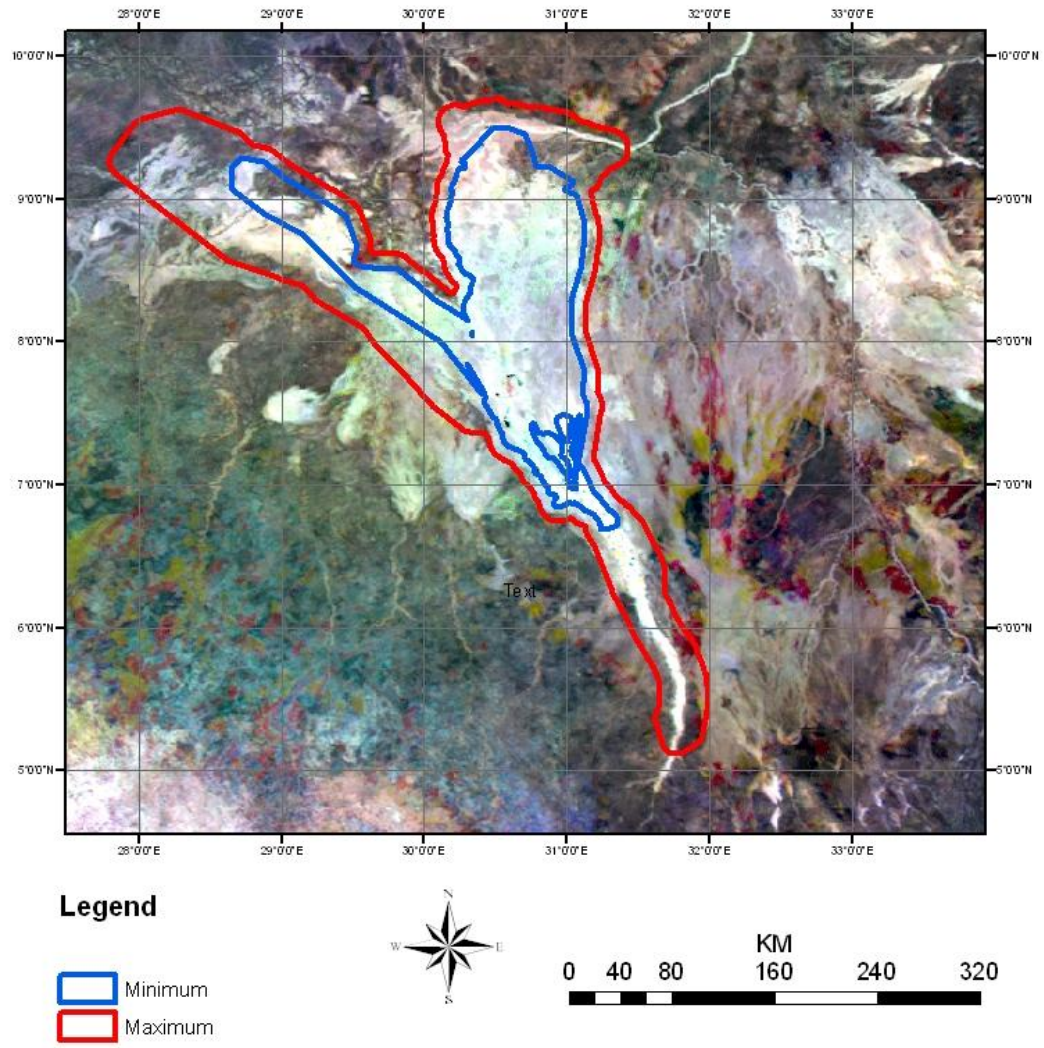


Fig.4.21: The Maximum and Minimum buffers that surrounding the extents of the Sudd area

Chapter 5. Sudd Hydrology And Climate

5.1 Introduction

The Sudd is a vast region of swamps formed by spillage from Bahr El-Jabal and its subsidiary channel, Bahr El-Zaraf. Bahr El-Jabal (named Albert Nile in its first reach) extends from the outlet of Lake Albert to its confluence with Bahr el Ghazal at Lake No. The Sudd receives flows from the equatorial lakes complex in addition to local runoff generated over the Bahr El-Jabal catchment. There is also some spillage from Bahr El-Ghazal catchment towards the Sudd (Sutcliffe and Parks, 1999). After Lake No, the combined river flows to the east to meet the Sobat, flowing from the east to the west, just above Malakal. The Sudd outflows, which include a small contribution from Bahr El-Ghazal basin, are combined with the outflows from the Sobat to form the White Nile flows at Malakal, Figure 5.1 (see ElShamy 2006).

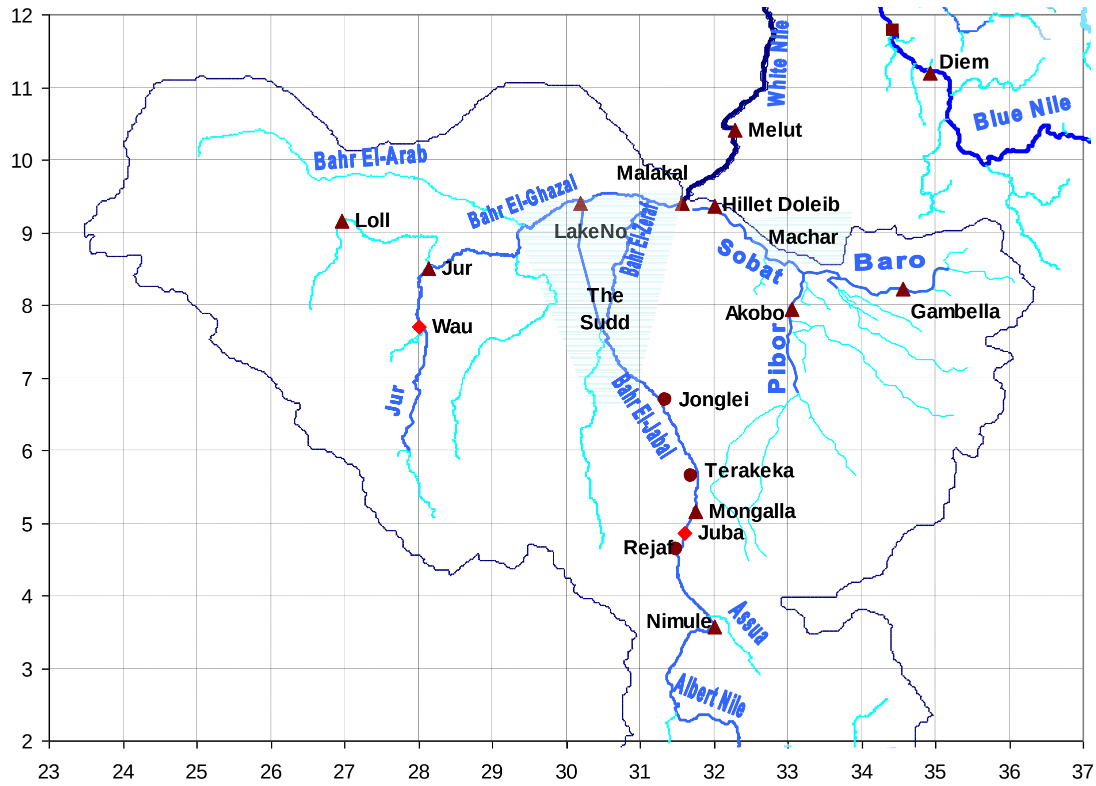


Fig.5.1: Location Map of the Sudd region showing important flow gauges (triangles) and cities (circles) - source: Elshamy (2006)

5.2 Analysis of Historical Data

To study the hydrology of the Sudd region, the inflows and outflows of the region need to be determined. For inflows, Mongalla is the key gauging station where the river is contained within a single channel as it enters the Sudd. Outflows should be measured at Lake No but the record for this station is too short and unreliable. The most reliable gauge in the region is Malakal below the confluence with Sobat. Neglecting the contribution of Bahr El-Ghazal, the outflows of the Sudd can be obtained by deducting the outflows of the Sobat at Hillet Doleib from the total flow at Malakal.

Figure 5.2 shows the annual series at the three stations for the period (1905-1982) while Figure 5.3 shows the annual series of losses over the region obtained by deducting the flows of the Sobat at Hillet Dolieb and the Albert Nile at Mongalla from those at Malakal.

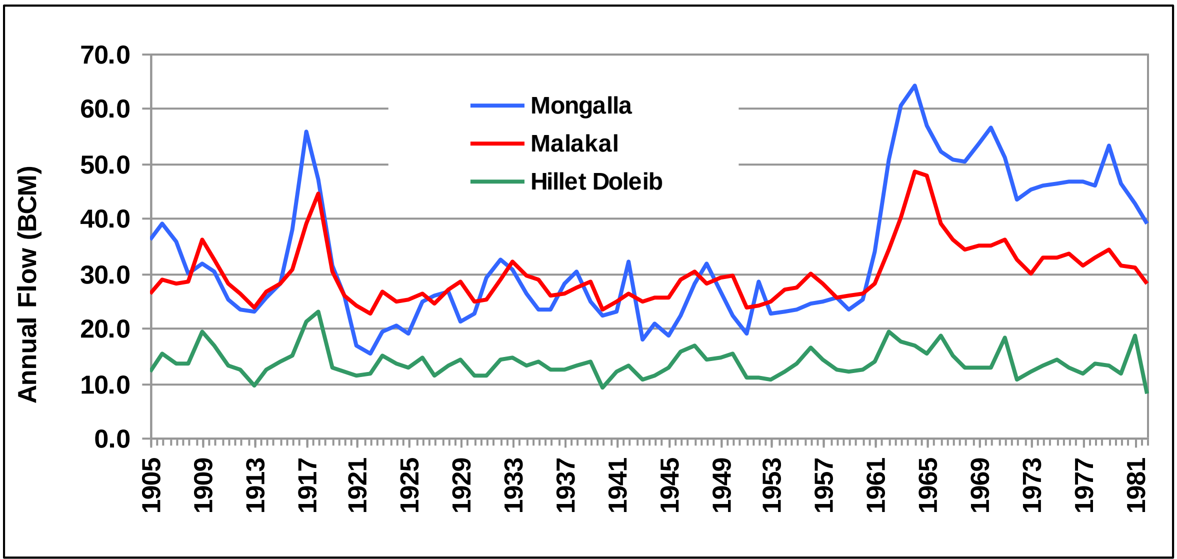


Fig.5.2: Annual flow time series at the key stations in the Sudd region (1905-1982)

Over the available period of record, the average annual flow for Hillet Dolieb ranged between a minimum of 8.2 (in 1982) and 23.1 BCM (in 1918) with relatively moderate inter-annual variability. On the contrary, the other two stations exhibited much higher ranges with some sharp peaks (e.g. in 1917/1918) and jumps (in the early 1960s). The maximum annual flow occurred in 1964 for both Mongalla (64 BCM) and Malakal (48.7 BCM) while the minimum occurred for both stations in 1922 with values of 15.3 BCM and 22.6 BCM for Mongalla and Malakal respectively. The average annual flows for the three stations amount to 13.7, 33.0, and 29.6 BCM for Hillet Doleib, Mongalla, and Malakal respectively while the standard deviations of annual flows amount to 2.66, 5.29, and 12.36 BCM for the three stations respectively.

The annual series of Mongalla and Malakal are close to each other's up to the 1960s when Malakal flows became much lower than those at Mongalla. This has been reflected in a large and sustained increase in the losses over the Sudd region (See Figure 5.3) nearly tripling from an average of about 10.5 BCM/yr over the period 1920-1960 to about 28.5 BCM/yr over the period 1961-1982. The period before 1920 was characterized by a high peak loss in 1917 reaching about 38 BCM which is nearly the same value reached in 1963 with the difference that large losses were sustained after 1963 till the end of record. The mean loss over the whole period amounts to 17 BCM/yr with a standard deviation of 9.3 BCM which is more than half the mean indicating large inter-annual variability. Correlation analysis shows that the losses over the Sudd are highly influenced by the inflows at Mongalla (with a correlation coefficient of 0.97 for the annual series 1905-1982). The losses, including local rainfall contribution, amount to about half the inflow measured at Mongalla.

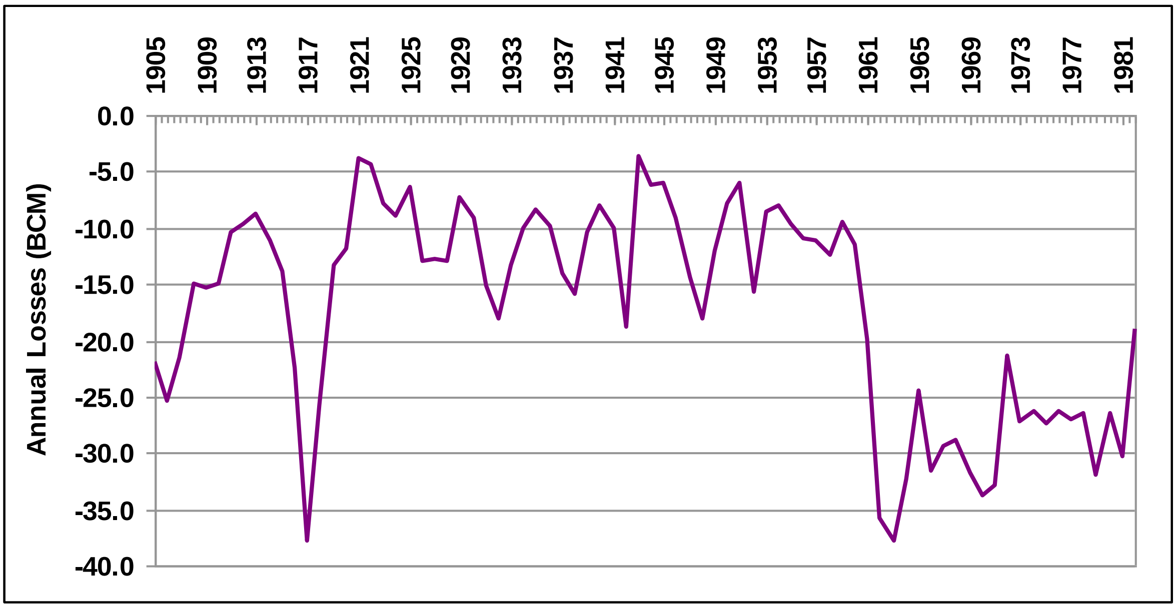


Fig.5.3: Annual loss time series over the Sudd region (1905-1982)

Figure 5.4 shows the average hydrographs of the three stations over the period 1940-1982 for which monthly flow records are available. The Hydrographs indicate the close correspondence in seasonality between flows at Malakal and Hillet Dolieb. The effect of the nearly steady outflow from the Sudd (Malakal – Hillet Doleib) is to raise the Malakal hydrograph while maintaining similar seasonality to that at Hillet Doleib. The loss over the Sudd, however, has some seasonality as it peaks in summer (August) with the peak of Mongalla inflows and reaches some minimum in winter (December – February). This seasonal pattern is also linked to local rainfall as shown below.

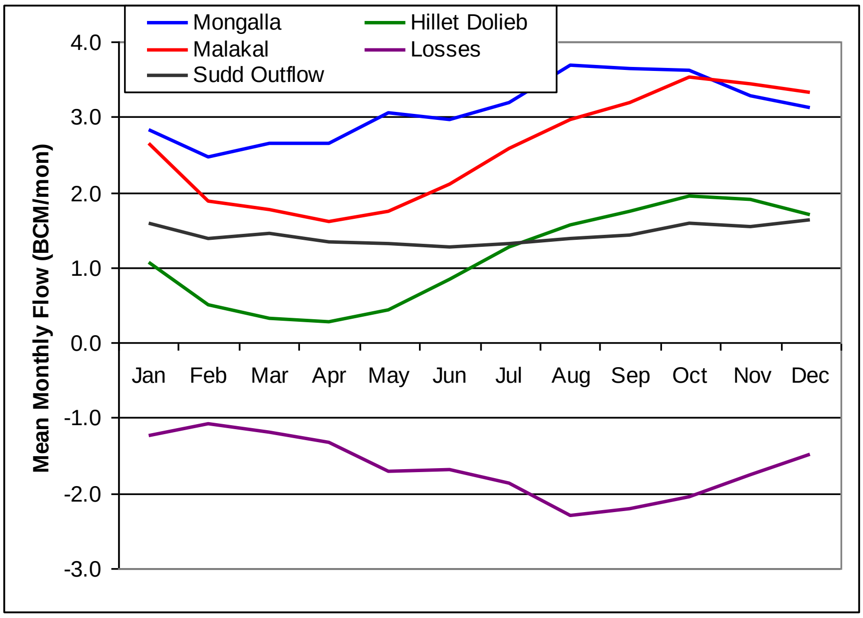


Fig.5.4: Average monthly hydrographs at the key stations and of Losses over the Sudd region (1940-1982)

Figure 5.5 shows the annual time series (1940-1982) and the mean monthly distributions of the mean areal precipitation (MAP) respectively for the three corresponding sub-catchments: the Equatorial

Lakes till Mongalla, the Sobat at Hillet Doleib, and the Whole White Nile Basin up to Malakal (including the Sobat, Bahr El-Jabal and Bahr El-Ghazal) and for Bahr El-Jabal between Mongalla and Malakal (i.e. local rainfall over the Sudd region). MAP is calculated for each sub-catchment as a spatial average over the whole respective catchment area from gridded (interpolated) maps based on available monthly rain gauge data. The annual series show maximum for all three areas occurring in 1961 which reached 1545, 1128, and 1072mm for the three sub-catchments (Mongalla, Hillet Doleib, and Malakal) respectively but this is not observed for the Sudd region itself. This high rainfall occurred mainly over the Equatorial Lakes and the southern parts of the Sobat. The average MAP amounts to 896mm/yr for the whole area at Malakal and 1162mm/yr up to Mongalla. The average over the Sobat is about 924mm/yr while that over the Sudd region amounts to about 800mm/yr.

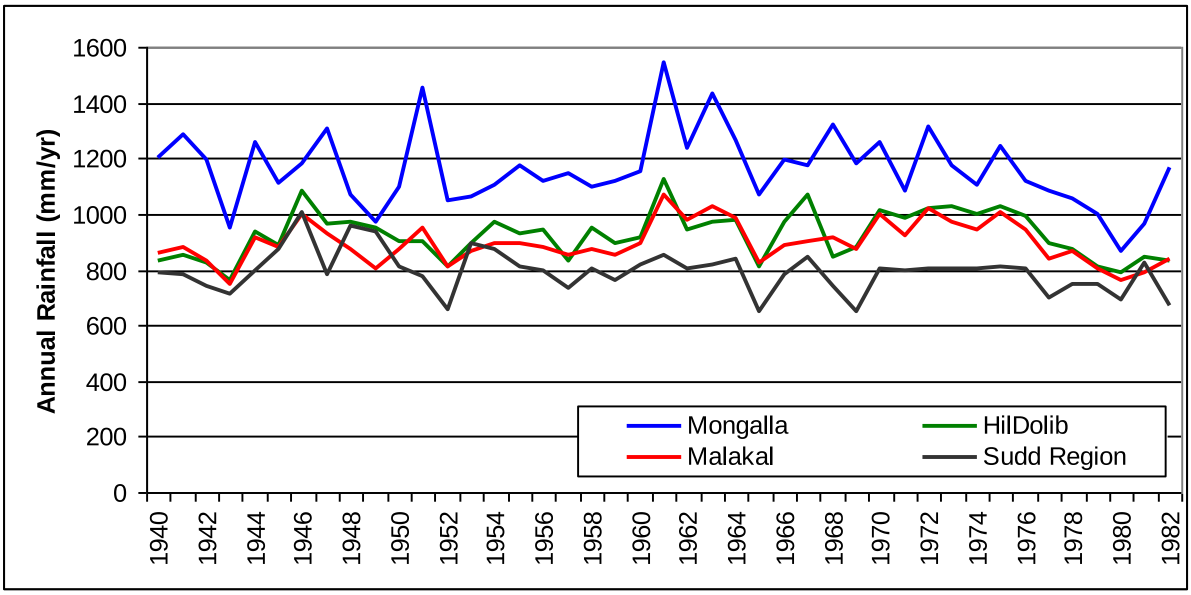


Fig.5.5: Annual mean areal precipitation (MAP) for key sub-basins to the Sudd region

The correlation coefficients between annual flow series and their corresponding rainfall series are generally low. The correlation between rainfall and flow at Mongalla is only 0.08 reflecting the effect of storage in the Equatorial Lakes. For the Sobat at Hillet Doleib and the Whole White Nile at Malakal, the correlation is higher (0.33 and 0.27 respectively) but still on the low side due to the effect of swamps in the Sobat and the additional effect of the Sudd for Malakal. The correlation between Sudd losses and local rainfall over the region is also low at 0.21 giving less importance to local rainfall contribution to losses compared to inflows.

Up to Mongalla, rainfall is bi-modal (Figure 5.6), a characteristic of equatorial rainfall, with a high peak in spring and a smaller one in Autumn. Rainfall over the Sobat is uni-modal with a broad peak during Spring and Summer. In fact, the Sobat has tributaries (those originating in Northern Uganda and Southern Sudan) with bi-modal rainfall distributions and others (those originating in Western Ethiopia) with uni-modal distributions. Thus the resultant rainfall over the whole catchment shows some integral of those two patterns. Rainfall over the Sudd region itself is highly seasonal peaking in August and nearly diminishes during winter. The integration of these rainfall distributions for the whole region at Malakal results in a bi-modal distribution but with a high peak in Summer (from the Sobat and the Sudd) and a closer peak during spring (corresponding to the higher spring peak observed at Mongalla).

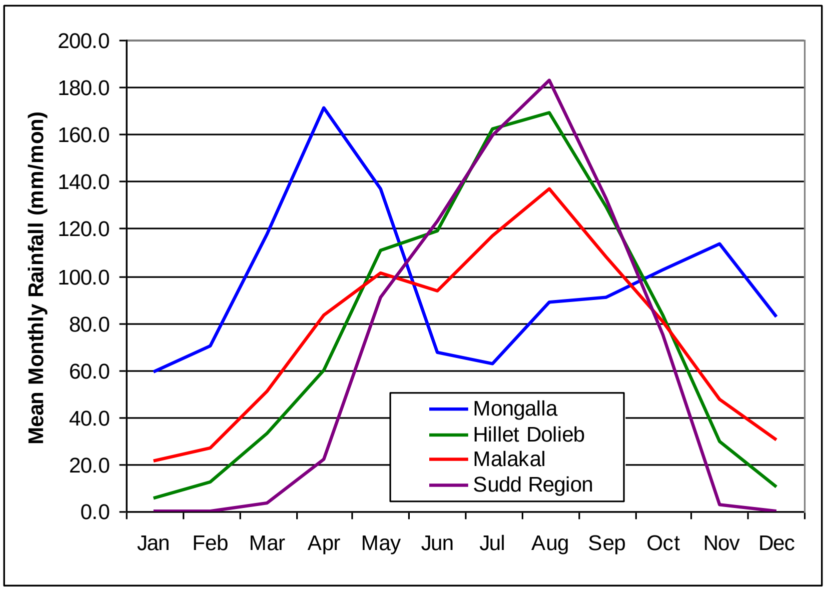


Fig.5.6: Mean monthly areal precipitation (MAP) for the key sub-basins to Sudd region

Figure 5.7 attempts to look at the mean distributions of the various water balance components of the Sudd region. As stated earlier, the outflow is nearly constant throughout the year averaging about 1.4 BCM/month. The high correlation between losses and inflows (at Mongalla) is observed in the distribution but there is also close correspondence between the hydrograph of losses and the distribution of rainfall. Losses reach their maximum during August when rainfall peaks and reach the winter minimum when rainfall diminishes. Thus, despite the low correlation of losses to rainfall on annual basis, the rainfall seasonality affects the seasonality of the losses because excess rainfall contributes to the seasonal variation of swamp area. In addition, there is close correspondence also between losses and PET (potential evapotranspiration obtained from climatological maps within the Nile Forecast System) although some recent research (Mohamed et al., 2004) indicates that actual evapotranspiration is far less than potential during the dry season.

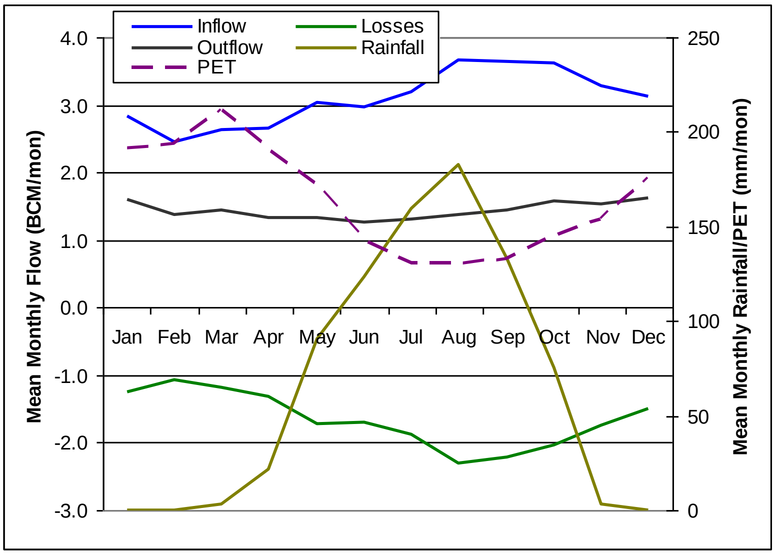


Fig.5.7: Water Balance Components of the Sudd

5.3 Hydrological Modeling of the Sudd

The objective of this exercise is to attempt building a hydrological model of the Sudd that is capable of predicting the swamp area and/or the Sudd outflow. Such a model would be a useful first step to evaluate the impacts of climate and land use changes over the area.

5.3.1 Review

Sutcliffe and Parks (1987) presented a simple water balance model of the Sudd swamps which showed close correspondence to a few estimates of the area that were available at that time. The average annual area of the swamps over the 1905-1980 periods was estimated as 21,000 km^2 and ranged between 12,900 and 28,900 km^2. Travaglia et al. (1995) applied a methodology based on the thermal inertia difference between dry and wet lands using data from the National Oceanic Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR). They defined the seasonal and inter-annual variation of the Sudd area between 28,000 and 48,000 km^2 during 1991–1993. Mason et al. (1992) used the thermal channel of METEOSAT to estimate the Sudd area during the period 1985–1990 between 8,000 km^2 at its minimum and 40,000 km^2 at its maximum. Mohamed et al. (2004) used the Surface Energy Balance Algorithm for Land (SEBAL) of Bastiaanssen et al. (1998) to estimate the evapotranspiration from the swamps and showed that it is much lower than open water evaporation (taken by Sutcliffe as 2150 mm/year). These results indicated larger swamp area if compared to that usually reported (38,000 km^2 on average).

With the increased availability of remote sensing data, a time series of the areal extents of the Sudd were obtained (see Chapter 4) covering the period 1999-2006 at 10-day time step. This dataset is utilized to calibrate the simple Sutcliffe and Parks (1987) swamp model to test its applicability under conditions different from those originally used by its developers. The following sections describe the model and its data requirements and then attempts to calibrate it using the areal extents dataset. The time step was selected to be one month rather than decadal to reduce the amount of data processing and modeling because the modeling required a lot of effort especially to deduce the inflow and outflow time series as explained below.

5.3.2 Hydrologic Model

The starting point to model the hydrologic behavior of the Sudd swamp is the water balance equation:

$$\Delta V = (Q_{in} - Q_{out} + (P - E) \times A) \times \Delta T - r\Delta A \qquad (1)$$

where:

V: Water volume stored in the swamp (L^3)
Q_{in}: Inflow discharge (L^{3}T^{-1})
Q_{out}: Outflow discharge (L^{3}T^{-1})
P: Precipitation rate (LT^{-1})
E: Evaporation (LT^{-1})
A: Swamp Area (L^2)
ΔT: Time Step (T)
r: soil moisture recharge (>0 if ΔA>0, =0 otherwise) (L)
Δ denotes change

If all the components of the equation are known (inflow, outflow, and rainfall and evaporation rates), a relationship between the swamp area and volume is required in order to solve the problem.

Assuming that the swamp acts as a linear reservoir, then $A=kV$, where k is the reservoir constant (actually the reciprocal of the water depth in case of linear reservoirs).

Considering a unit time step (e.g. one month), and substituting for V, the discretized equation becomes:

$$V_{i+1} = V_i + Q_{in} - Q_{out} + (P - E) \times (A_i + A_{i+1})/2 - rk(V_{i+1} - V_i) \quad (2)$$

By rearranging equation (2) and solving iteratively for A, the time series of the areal extents of the marsh can be determined. The soil moisture recharge is assumed to vary from an initial value at the start of the wet season with the total net rainfall.

5.3.3 Data Collection and Processing

In order to calibrate this model using the derived areal extents dataset, all components of the balance must be known. These are the inflow and outflow and rainfall and evaporation rates over the same period (1999-2006).

Rainfall

Rainfall was obtained as an areal average from the daily merged satellite-gauge dataset of the Nile Forecast System (NFS) (Nile Forecast Center, 2007). The details of how this dataset is created can be found in Elshamy et al. (2009) and Nile Forecast Center (Nile Forecast Center, 1999). The calculated mean areal precipitation over the swamp area corresponds to a fixed swamp area; i.e. the dynamics of the area modeled here is not taken into account when rainfall is averaged. However, this should have a huge effect and was common to previous modeling attempts of Sutcliffe and Parks (1987) who used rainfall averaged from 3 stations around the Sudd. Mean annual rainfall over the study period varied between 636mm in 2000 and 973mm in 2003 with an average value of 818mm. Rainfall starts in April and peaks in August while the months November till March are mostly dry (Figure 5.8).

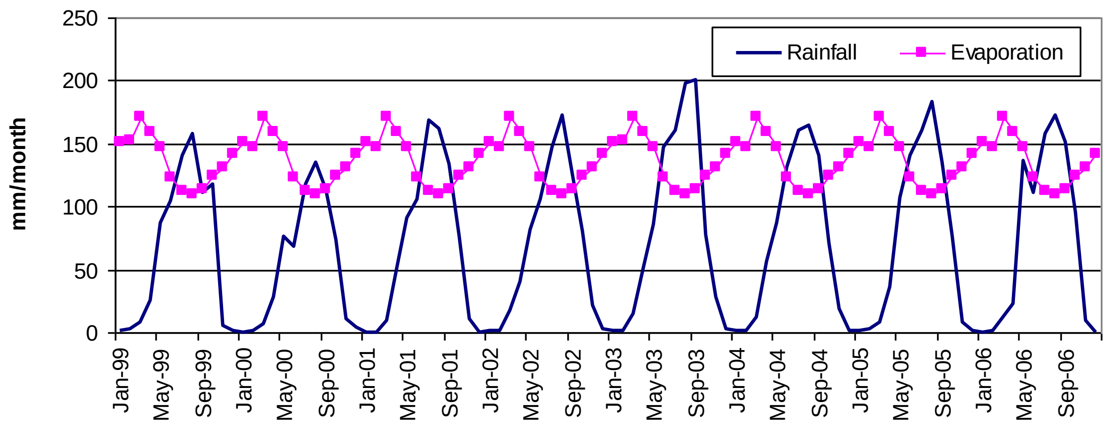


Fig.5.8: Monthly Spatial Mean Rainfall and Evaporation Timeseries over the Sudd Swamp

Evaporation

Evaporation is also taken from the NFS database in the form of 12 monthly long-term gridded maps of reference crop evapotranspiration. The source or averaging period of these data could not be traced from the available documentation. However, comparisons of the annual PET map with a map based on reference crop ET data from the FAO CLIMWAT database (FAO, 2000) revealed close resemblance (LNFDC, 2008), which is to be expected due to the involvement of the FAO in NFS development. Although the inter-annual variability of evaporation may play a role in the water balance, this is the dataset available. Global datasets (e.g. CRU TS 2.1 - Mitchell and Jones, 2005) do not cover the 1999-2006 period.

The mean annual total evaporation over the Sudd region amounted to 1963mm which is about 10% less than the value used by Sutcliffe and Parks (1987) which amounted to 2150mm calculated as open water evaporation. Mohamed et al. (2006) estimated the total annual actual evaporation for 1995, 1999 and 2000 as 1460, 1935 and 1636mm respectively with little seasonal variation. NFS PET peaks in the end of the dry season while the lowest value coincides with the rainfall peak in August. For the current exercise, the NFS values were initially used but better matching was obtained using scaled values totaling 1636mm taken as a medium value from Mohamed et al. (2006).

Inflow

The inflow to the Sudd is usually taken as the discharge at Mongalla. Unfortunately, level measurements at Mongalla stopped in 1983 with the eruption of war in Southern Sudan. Records from nearby Juba station, about 50 km upstream, were obtained for the study period and used to estimate the flow at Mongalla. Levels at Juba were measured since 1925 and published in the Nile Basin series. Measurements stopped in 1991 but were resumed again in 1997. Levels at Juba resemble those of Mongalla closely as shown in Figure 5.9, enabling the estimation of Mongalla levels or discharges from those measured at Juba. However, there is an upward trend in Mongalla levels that is not seen in Juba. Thus, to avoid this effect as much as possible, the last few records (1978-1982) were only used in the estimation procedure. Figure 5.10 shows the levels at Juba for the 1997-2006 period which shows little variability during the period 2001-2003 which seems strange. There is a lowering trend thereafter which is a result of the low levels of Lake Victoria during this period due to combined effects of drought and excess releases for power generation.

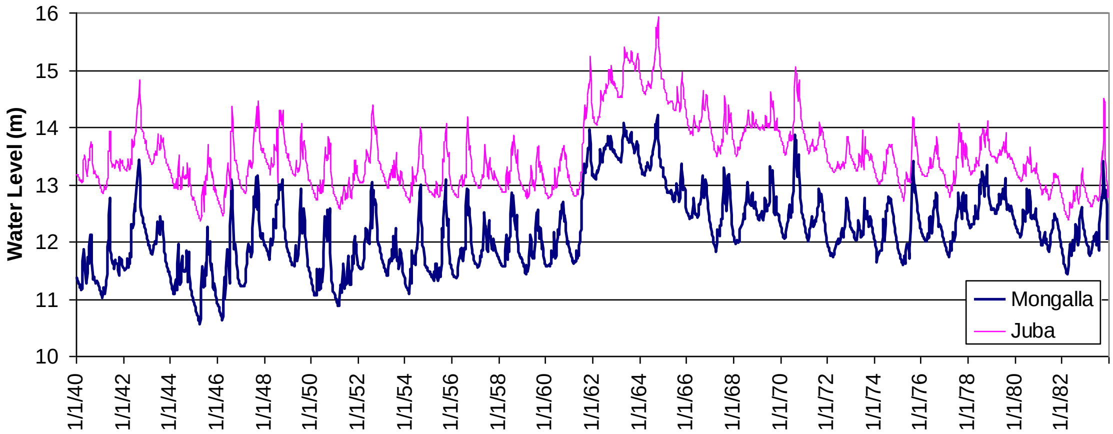


Fig.5.9: 10-day Water Levels of Juba and Mongalla on Bahr El-Jebel (1940-1983)

There are two possible methods for estimating flows at Mongalla from Juba levels: 1) to build a rating curve between Juba levels and Mongalla flows; 2) to first estimate Mongalla levels from Juba's then use a rating curve at Mongalla to estimate the flows. Although the first approach seems more direct, the second method was preferred because discharge and level measurements are available for Mongalla for the period 1940-1984 on certain dates while levels at Juba are available for this period as decadal means. A relationship between the levels at Mongalla and Juba was established based on measurements for the period 1978-1982 as shown in Fig.5.10:. Levels of 1983 were excluded because including them reduces the correlation.

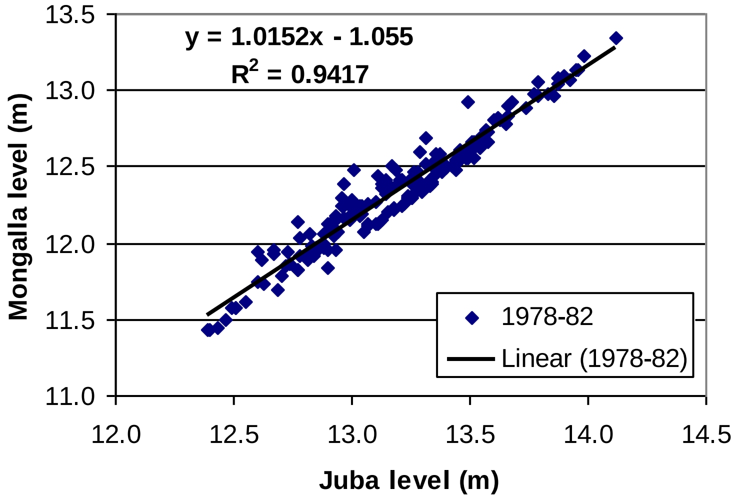


Fig.5.10: Relationship between Mongalla and Juba levels

The estimated levels of Mongalla based on Juba were then converted to flows at Mongalla using a rating curve obtained based on flow measurements at Mongalla. 127 flow measurements taken during the period 1970-1984 covering a wide range of levels (11.48 – 13.6m) and discharges (965 – 2580 m^3/s) which are only exceeded by the exceptional values occurring in the early 1960s after the rise of Lake Victoria levels. The rating curve (Figure 5.11) looked stable over this period and it was built by adding data gradually (stating from 1984 and going backwards) until the rating curve started to deviate and showed that it follows another relationship.

Using these two-tier procedures, the flows at Mongalla for the period 1999-2006 was obtained as shown in Figure 5.12. Using these relationships in a hindcast, the flow compares well till mid 1970s. Going backwards, deviations get larger (Figure 5.13) because of the Mongalla trend level that is not paralleled at Juba and thus the developed relationship is no longer applicable without proper adjustment.

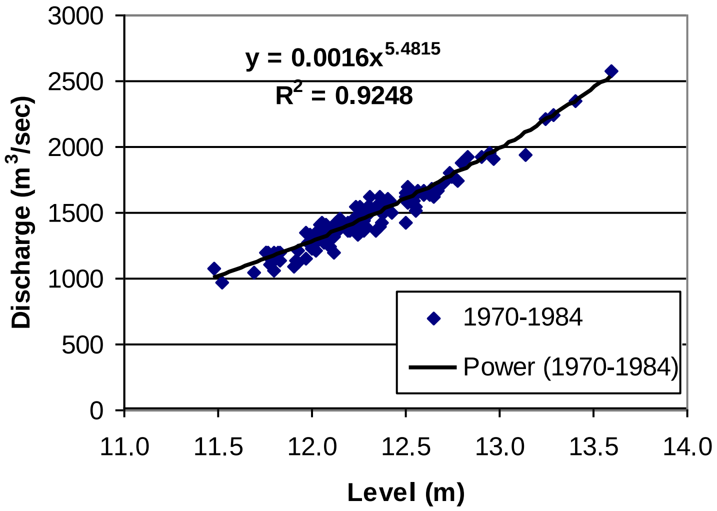


Fig.5.11: Rating Curve of Mongalla (1970-1984 data)

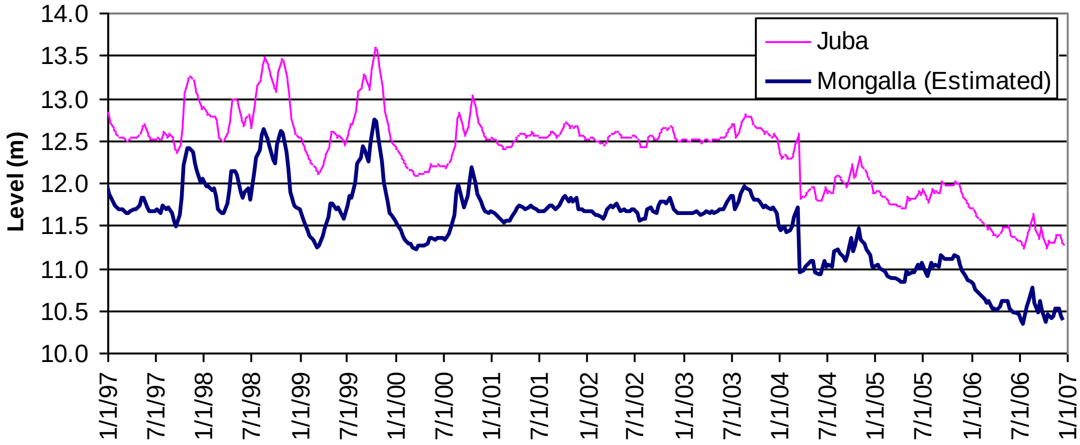


Fig.5.12: Juba levels and Estimated Mongalla levels (1997-2006)

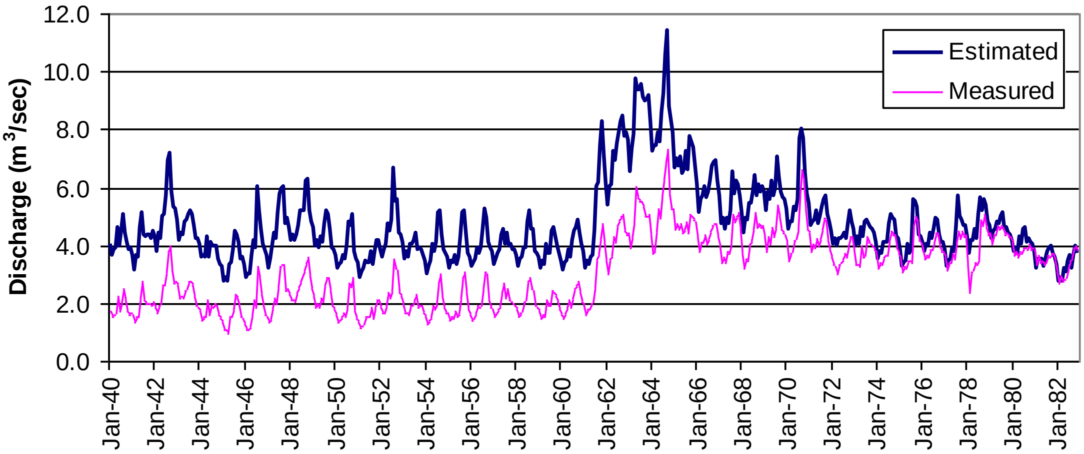


Fig.5.13: Estimated vs. Measured Monthly Flows at Mongalla

Outflow

The outflow from the Sudd swamps is not directly measured. As mentioned earlier, the next reliable gauge on the White Nile is Malakal whose flows include the contributions of the Sobat and Bahr El-Ghazal as well as the outflow of the Sudd (i.e. the contribution of Bahr El-Jabal). Neglecting the minute contribution of Bahr El-Ghazal, the outflow of the Sudd can be deduced by differencing the flows of Malakal and Hillet Doleib (the outlet of the Sobat).

The record at Malakal for the study period (1999-2006) is available and reliable. However, level measurements for Hillet Doleib stopped in 1983 due to the civil war in Southern Sudan. Although level measurements were resumed in September 1998, flows were not measured to develop updated rating curves. Since this resumption, there have been fairly long stoppages in 2001, 2002, and 2003 as well.

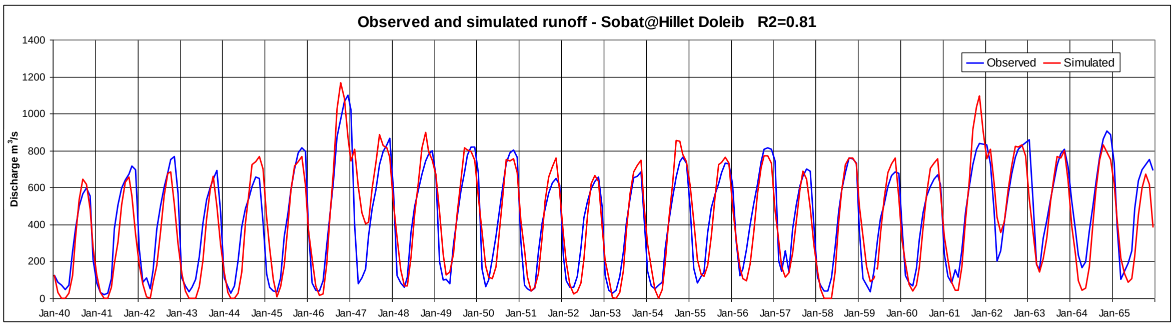
Historical rating curves at Hillet Doleib are looped (Shahin, 1985) and vary from one year to another. Given these annual variations, a general rating curve would not be appropriate. An attempt to develop rating curves for each decade was made but for the current study one needs to develop a rating curve from as recent data as possible. However, the number of flow gauging (taken from Nile Basin Vol II Supplements) during the period 1973-1984 amounted to 93, i.e. less than 9 per year in average, which hinders the development of proper rating curves for the rising and falling stages.

Thus, another approach had to be followed to estimate the flows of the Sobat at Hillet Doleib, namely, hydrological modeling. For this purpose a spreadsheet version of the HBV model (Killingtveit, personal communication, 2007) was utilized and modified to handle monthly time series data spanning several years (the original model handled daily data for each year separately).

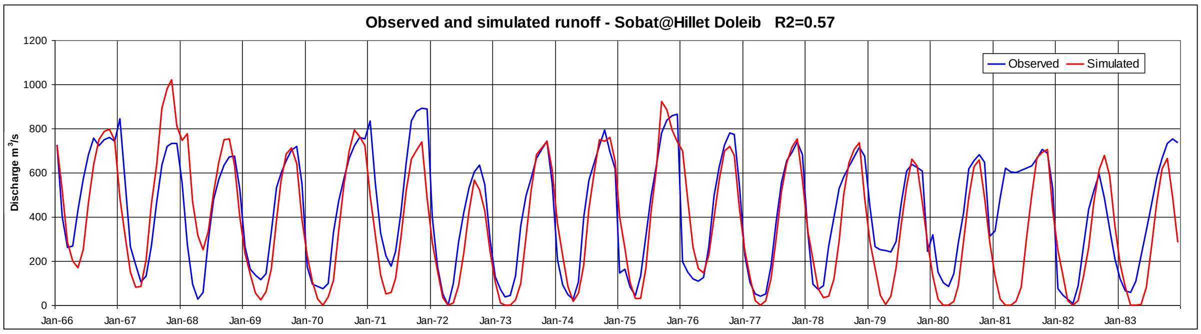
The HBV model (Bergström, 1994) is a rainfall-runoff model, which includes conceptual numerical descriptions of hydrological processes at the catchment scale. It can be applied as a lumped model for the whole catchment or in a distributed way. The model consists of a precipitation routine representing rainfall and snow, a soil moisture routine determining actual evapotranspiration, overland flow and subsurface flow, a fast flow routine representing storm flow, a slow flow routine representing subsurface flow, a transformation routine for flow delay and attenuation and a routing routine for river flow. The model allows for the existence of open water where rainfall in excess of evapotranspiration (which proceeds at the potential rate) is directly transferred to the lowest soil moisture zone which gives the longest delay characterizing lakes and swamps.

The HBV model requires temperature, precipitation, and potential evapotranspiration data to operate. Temperature data is needed mainly for snow accumulation and melt calculations and thus were ignored as these processes are absent in the selected basins. For precipitation and evapotranspiration, the mean areal precipitation and PET were taken from the NFS database as described above for the Sudd area. The database contains monthly data from 1940-1969 and then daily data from 1970 onwards with some gaps (1977-1983 and 1985-1988). Concurrent flow data is also available from the Nile Basin Vol IV Supplements up to 1983.

HBV has been calibrated for the Sobat basin at Hillet Doleib using flow records for the period 1940-1965. The record from 1966-1983 was then used for verification (Figure 5.14). The performance was fairly good for the calibration period but was reduced as expected for the verification period. The basin area was taken from the NFS as well an amounted to 241,762 km^2 of which 2.07% (5000 km^2) were set as open water to account for Machar marshes.



a) Calibration Period (1940-1965)



b) Verification Period (1966-1983)

Fig.5.14: Performance of the HBV in Simulating the Flow of the Sobat@Hillet Doleib

Then the model was applied to obtain the flows for the period 1984-2006. Flow results for the 1999-2006 period was compared to available levels and the match looks satisfactory (Figure 5.15). The correlation coefficient of the two monthly series is about 0.76.

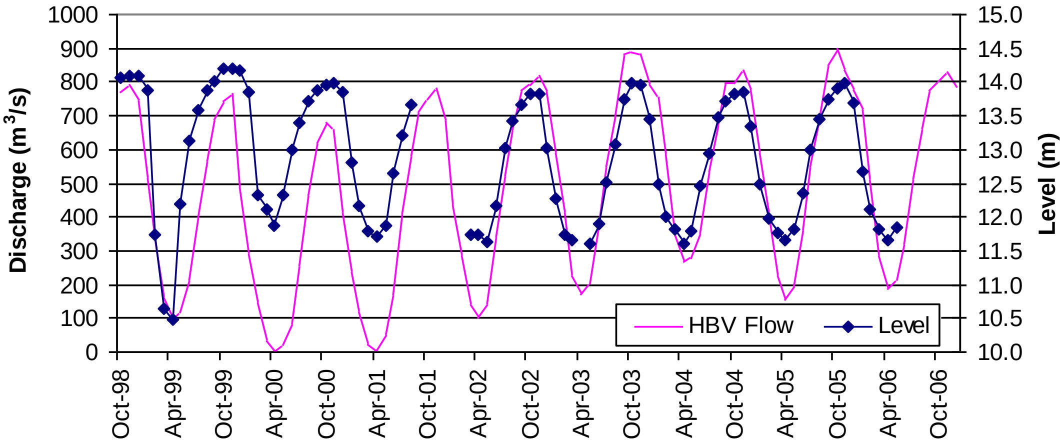


Fig.5.15: Simulated Sobat Flows vs. Level Measurements (1998-2006)

As mentioned above, the outflow of the Sudd is then obtained by deducting the estimated Sobat flow from those observed at Malakal (Figure 5.16). The flow at Malakal does not reflect the downward trend that can be seen at Mongalla (resulting for the downward trend of Juba levels – see Figure 5.12). The resulting Sudd losses are shown in Figure 5.17 compared for 1999 and 2000 with results taken from Mohamed et al. (2006) who predict higher losses due to predicting higher inflows at Mongalla. They estimated Mongalla flows from Lake Victoria outflows taking into consideration the contributions and losses from Kyoga and Albert basins and torrents.

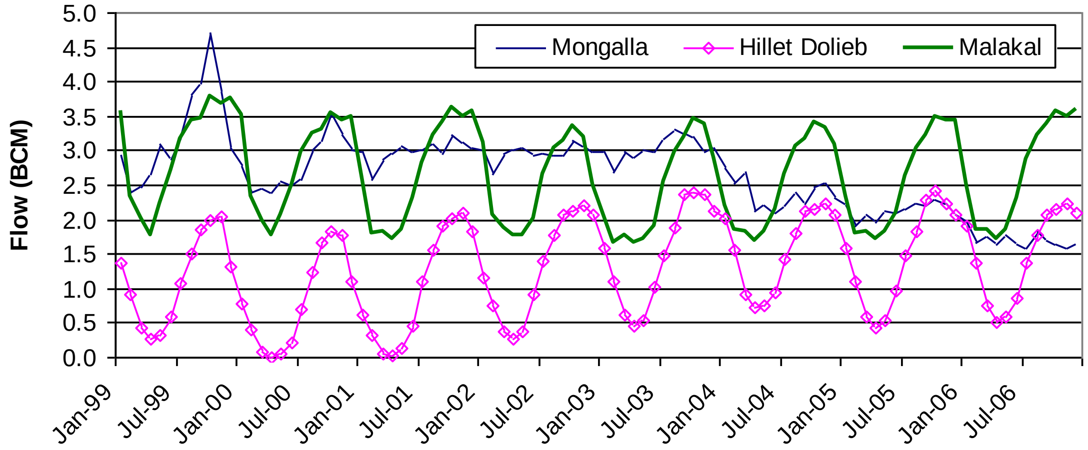


Fig.5.16: Flows at Mongalla, Hillet Doleib, and Malakal

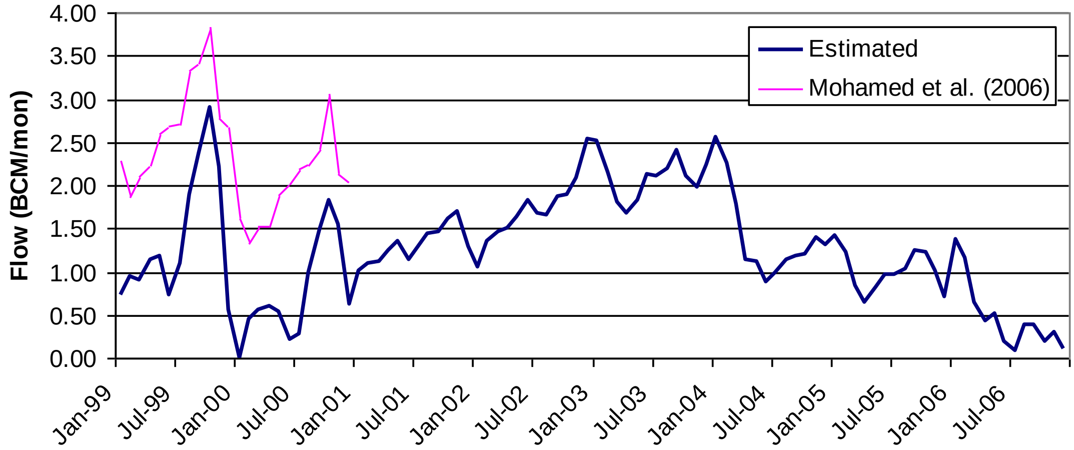


Fig.5.17: Estimated Monthly Sudd Losses

5.3.4 Swamp Model Results

Recognizing the mentioned uncertainties in the estimation of all elements of the water balance, the swamp model outlined above has been applied to the Sudd swamp for the purpose of simulating the variations of the areal extents of the swamp. Before the results are discussed, the obtained time series of areas are presented (Figure 5.18). The area ranges between a minimum of about 20,000 km^2 to a maximum reaching 120,000 km^2 in some years. The seasonal fluctuations are characterized by a broad peak during the months of August – November coinciding with the peak rainfall (Compare Figure 5.8). The late recession of areal extents compared to rainfall is explained by the method used to obtain these areas which is vegetation index techniques (see Chapter 4). Vegetation will remain vibrant during the rainfall recession due to the high level of soil moisture storage. While the minimum area representing the permanent swamps seems reasonable, the maximum area seems too large. The average area of this dataset is about 69,000 km^2 which is about 80% more than that reported by Mohamed et al. (2006) (38,600 km^2) which is in turn 74% larger than reported by Sutcliffe and Parks (1999).

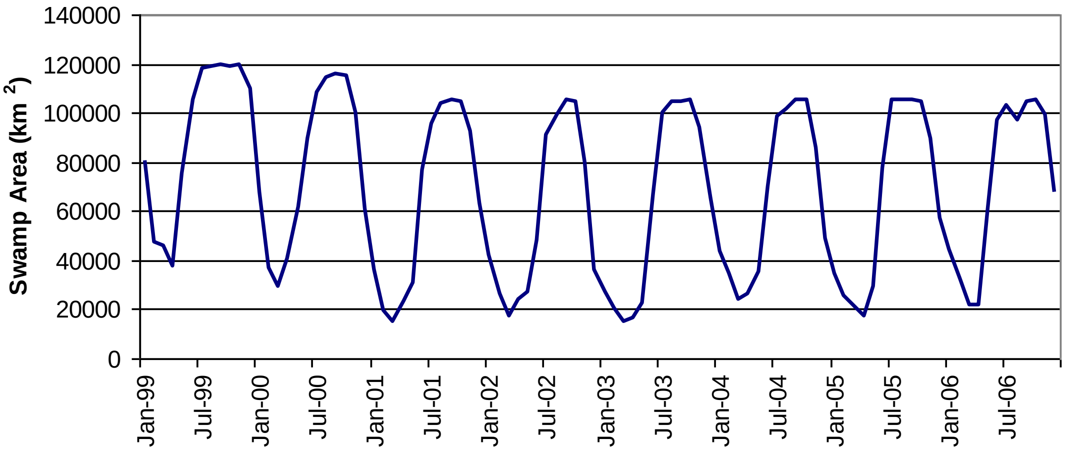


Fig.5.18: Monthly Time series of Swamp Areal Extents

The first attempts to apply the described swamp model using the areal extents as is resulted in unreasonable values for the parameters (k and r). Thus, it was assumed that only a fraction of the area was really swamp while the rest would be vegetation at its fringes. This fraction was found after a few iterations to range between 0.3 and 0.4. The model was then calibrated (using a fraction of 0.35) iteratively to obtain the best match with the area and the values of the k and r parameters (Figure 5.19). The optimized k and r values were 5.0m^{-1} and 0.07m respectively which are significantly lower from those suggested by Sutcliffe and Parks (1987) (1.0m^{-1} and 0.2m respectively). The calibrated value of k (=5.0) means an average depth of only 0.2m in addition to the low value of the soil recharge parameter r suggest the area, or the area fluctuations are too large.

Regarding the model performance, it could only match the peak values in some years but could not reproduce the flat peaks. It also underestimated the peaks in 2000 and 2006 and highly overestimated the peak in 2003. Rainfall was relatively low in 2000 and relatively high in 2003 while the inflows were on the low side in 2006 which may explain these results. Thus, the model is much more responsive than observations to inflows and rainfall. Even after excluding the very high simulated peak in 2003 from the optimization, the resulting R^2 is not encouraging (-1).

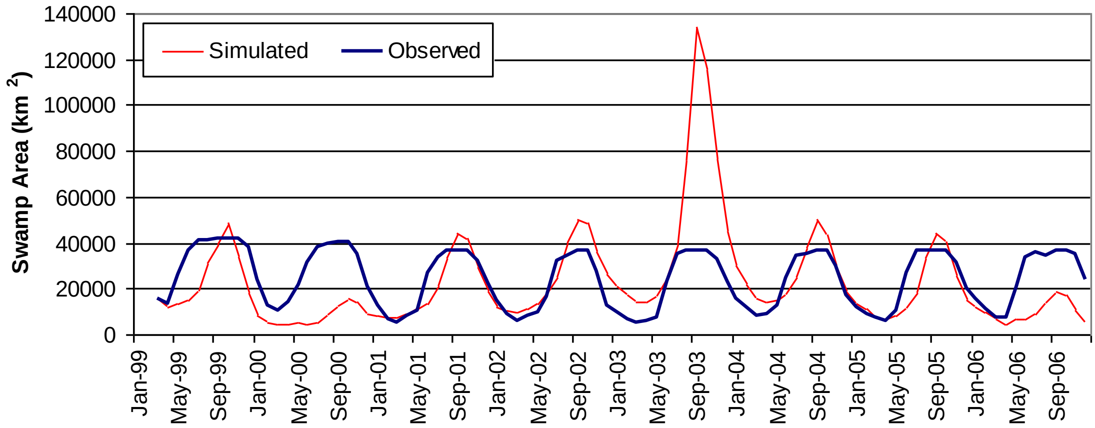


Fig.5.19: Simulated vs. Observed Swamp Area

The model was then applied to the historical record from 1940-1983 (Figure 5.20) but it failed using the calibrated parameter values above (negative areas). Then, the values given by Sutcliffe and Parks

(1987) were used and gave the shown fluctuations. It is clear that the peaks are sharp and that the average area almost tripled after the sudden rise of Lake Victoria levels in the early 1960s.

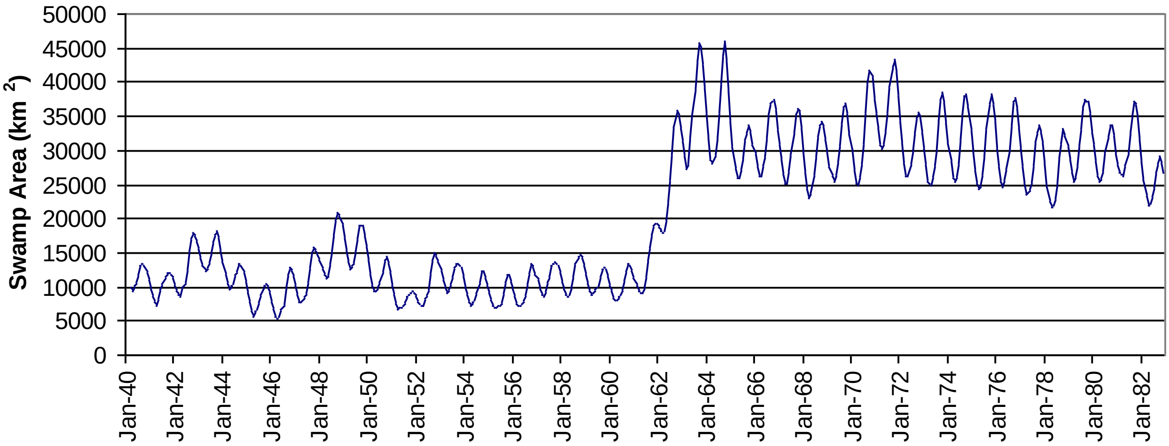


Fig.5.20: Modeled Swamp Area for 1940-1983

5.4 Discussion and Conclusion

Based on the very limited data available over the Sudd region, a statistical analysis was conducted to analyze the hydrological behavior of this area. The Sudd receives flows from the equatorial lakes complex at Mongalla, the runoff of Bahr El-Jabal and some spills from Bahr El-Ghazal sub-catchments, in addition to local rainfall over the area. The Sudd outflows, which include a small contribution from Bahr El-Ghazal basin, are combined with the outflows from the Sobat, at Hillet Doleib, to form the White Nile flows at Malakal which is the most reliable flow gauge in the area. The available observed flow records at both Mongalla and Hillet Doleib (1905-1982) were used to analyze the flow gains/losses over the Sudd by subtracting the Sobat and Mongalla flows from those at Malakal. These records were used in conjunction with the Mean Areal Precipitation (MAP) over the catchment, as derived from the gridded rain gauge data, to assess the relative influence of local rainfall and inflows on Sudd ouflows. The low correlation between the observed annual losses of the Sudd and MAP (0.21) indicates the less importance and effect of rainfall over the Sudd area in terms of the annual amount of losses. However, the correlation between the Sudd losses and Mongalla flows is about 0.97 indicating the high dependence of Sudd losses on inflows at Mongalla. The rainfall mainly affects the seasonal distribution of losses. The combined contribution of Bahr El-Jabal and Bahr El-Ghazal is negative over the available time period. It could be noticed that the observed losses increased significantly in the early 1960s in response to the increased inflows from the upper catchment following the dramatic 2.5 m rise in Lake Victoria level and were sustained at a high level thereafter.

The modeling exercise is an early attempt (key knowledge) to model the variations of the Sudd swamp area following the simple approach of Sutcliffe and Parks (1987). They had only a few observations to check the model with but they succeeded to obtain a good match. In this analysis, and probably for the first time, remote sensing provided a time series of the areal extents of the swamps which were used to calibrate the model. However, the model performance was relatively poor. There are several reasons for that including large uncertainties in all elements of the water balance. Inflows at Mongalla are estimated from Juba levels. Although the rating curve of Mongalla seems stable and the relationship between Mongalla and Juba levels is reasonable, an upward trend in the levels at Mongalla that is not matched at Juba may have spoiled the estimates. Outflows are also problematic where the Sobat flows at Hillet Doleib had to be estimated through a hydrological model. The inter-annual variations of evapotranspiration over the region were not accounted for either. Rainfall may be the least uncertain element; however, the quality of the satellite-based estimates needs to be validated over this region. Given the limited number of rain gauges in such region, this is not an easy task. In addition to all these factors, the areal extents or fluctuations may have been exaggerated as the vegetation on the fringes may contaminate the data. This requires ground truthing which is extremely difficult in such large area with many remote, inaccessible, and dangerous locations. Last but not least, the model structure may be too simple for this exercise.

There are several future suggestions to improve the modeling of the Sudd extents. These include: calibration of satellite rainfall using available rain gauges; estimation of inter-annual variations of evapotranspiration over the region using global datasets such as CRU TS 2.1 or algorithms like SEBAL and METRIC; better estimation of inflows and outflows through hydrological modeling; and more complicated swamp model. Hydrodynamic modeling (Petersen et al., 2008) may also be more appropriate but it requires much more data inputs.

Chapter 6. Development Interventions

6.1 Introduction

Ecosystem management is to preserve ecological functions and processes while meeting human needs. This chapter intends to introduce some ideas covering short and long terms management that improving the livelihood of the population of the Sudd without compromising the diverse ecosystem. To achieve these requirements, local, national, and international participations should be compiled for sustainable management. In addition, the initiated and existing projects and programs should be taken into consideration to identify priority areas of interventions. This is initiated by promoting of local development through coordinating the multi-actor activities and pressures. In addition, many issues should be investigated such as successful practices in the areas, available skills, and community requirements. The intended development should be organized in the scope of Ramsar principles explained in chapter 3.

6.2 Development requirement and options

Many issues and actions need to be managed. Some of them can be summarized in the following:

1. Education is a major element for improving job opportunities and standard of life.
2. Improving techniques will accelerate better production of agriculture, forestry, animal resources and fishing.
3. Awareness and responsibility allocation among different stakeholders and various levels must be created to overcome the lack of understanding the value and function of the Sudd area
4. Media engagement to facilitate public awareness
5. Stakeholder analysis taken into consideration the distant stakeholders
6. Establish proper legislations for human and environments
7. Sustainable land use and land tenure system
8. Water management for better management of soil and water conservation practices
9. Mechanism for mitigating disasters
10. Inventory and base map for available resources
11. Promote marketing of livestock at national and regional levels
12. Overgrazing management
13. Design livestock movement and raise awareness
14. Development of tools to influence policy makers
15. Conflict resolution mechanism through mitigation of over fishing and grazing
16. Define the tourism potential and capacity, Predict impacts, and apply safe environmental practices in tourism activities
17. Policy safeguard for protected area
18. Avoid intervention and disturbance of migration routes
19. Impact assessment for any new project or exploration
20. Apply mitigation measures in suitable time
21. Establish quick technique to assess water pollutant
22. Establish an irrigation system for efficient management
23. Health facility for human and ecosystem

6.3 Jonglei canal project

The Jonglei Canal project in the Southern Sudan is considered as a water resources development project as well as a way for promoting and modernizing the social standards and economic life of the population in the project area. The primary purpose of the project is to conserve water for irrigation which would otherwise be lost to evaporation in the Nilotic Sudd swamps. Table 6.1 indicates the expected benefit after the project completion.

Table 6.1: Mean monthly timely discharges reaching Malakal (x 10^6 m^3) and the benefit realized after regulation of Lake Albert and the Sudd diversion canal.

Malkal	Contribution of				White Nile		
Date	**Sobat**	**Jebel**	**Canal**	**Torrents**	**Regulated**	**Natural**	**Grain**
December 21-31	44	25	29	2	100	87	13
January	26	25	49	0	100	69	31
February	13	32	50	0	95	5	40
March	9	32	50	0	91	49	42
April	8	32	50	0	90	46	44
May	14	32	50	2	98	50	48
June 1-20	27	25	12	5	59	62	7
Total						814	225
Total Gain at Malkal					643		

Project excavation began in June 1978 (Renold Bailey and Stephen Cobb, 1984) when complete the canal 360 km long, 50 m wide and 4 m deep will divert 20 million cubic meters or more of the daily flow of bahr el Jebel around the swamp and return it to the White Nile at the Sobat confluence. Since the canal is expected to have considerable impact on the water regime and ecology of the Sudan Plain and its inhabitants, several pre-completion survey were commissioned by the government of Sudan with financial aid from the European Development Funds. Four investigations were carried out; the first three were concerned with the range of ecology survey and investigation of livestock and water supplies and took place between 1979 and May 1982. The following section discusses the situation in the Sudd area before and after the project according to the report of the permanent technical committee of Egypt and Sudan in 1980.

6.3.1 Pre-Project Situation

The dominant economic activity is traditional livestock production pastoral nomadism while crop production is geared to subsistence needs. This pattern of economic activity is dictated to a large extent by the topography, climate, and hydrology of the area. The land area ranges from highland in the East which is comparatively flood-free, even during the rainy season, to intermediate land which is subject to heavy flooding during the wet season but waterless in the dry season. Below that there is "*toich*" land which comprises the flood plains of the river and its main channels. This land derives its moisture through its being inundated by river over spilling during flood season. Below the level of the "*toich*" are the riverine marshes and permanent swamps known as the "Sudd region" This East-West land classification by elevation pertains to the flood plain area which constitutes the main part of the Jonglei area. To the North there are the semi-arid and arid areas with declining average rainfall. Below it there is the iron stone region, an area characterized by higher average rainfall, greater slope and more permeable soil. As has been pointed out by the Jonglei investigation team that one of the most obvious and significant features in the jonglei is the scarcity of ground high enough to be relatively free from flood during the rainy season. Such areas are of particular significance from the human point of view since they are the only refuge available for the occupants and their livestock, and their distribution has important effects on the demography of the whole area. In this extremely flat country it is not necessarily the relative level of the land which alone determines its susceptibility to flooding but the slope and soil permeability as well as vegetation are factors of equal or even greater importance[1]. During the rainy season, from April or May until December, the river banks and adjacent plains are over flooded and "creeping floods" moving from South-East to North West. Accordingly, the inhabitants are forced to move to their settlements on the highlands where they take refuge from the floods and biting insects. There, they practice rainfed crop agriculture around their scattered permanent settlement villages. Towards the end of the rainy season, the cultivation season comes to its end, and crops would be harvested (see Figure. 6.1 for a typical migratory cycle). The trade and distribution systems are characteristic of substance system where most of production is for local direct consumption. Livestock is the main capital asset of the area. Average offtake amounts to between 12 and 15% per annum (sometimes reaching a level of 2%) commercial offtake amounts to 1% or less. The difference is accounted for by mortality (4.9%) meat for the owners (6.8%) and social and sacrificial purposes. Animals are sold only when cash is needed for marriage, hospitalization, buying of sorghum or other essential food, and the like. Barter trade is the predominant practice. Savings and investments are embodied in livestock holdings.

In the historical context of a non- monetized economy, certain institutions evolved which further reinforced the attractiveness of investment in livestock. Marriages were legitimized with the transfer of cattle, power and influence were acquired by the distribution of animals to clients, and rank was confirmed by the ability to provide animals to clients, and rank was confirmed by the ability to provide animals for slaughter or ritual occasion. A result of these institutions ownership of livestock assumed an overwhelming importance for social status, creating a strong preference for the pastoral way of life among both the beneficiaries and the victims of the system[2]. The area's physical, economic and social features complement and reinforce one another in an interlocking manner. Thus any major change in the areas physical structure would entail complemtary changes in the economic and social dimensions. The Jonglei Project has come at a time when compelling reason for change had already developed. Firstly, population growth, has led to overconcentration in the settlement highland areas and over cropping in the cultivated areas leading to serious soil erosion and productivity decline. If the area's subsistence demand for cereals is to be provided, a greater shift towards sedentary agriculture must be undertaken in new areas. The shilluks have moved a great deal in this direction.

Secondly, the accelerating growth in the size of the area's livestock herd (especially goats which are omnivorous) coupled with selective and prolonged grazing without any grazing rotation has led to major deterioration in pasture quality and is threatening the economies of the livestock industry and its future growth prospects. Thirdly, even if the problems of soil and pasture erosion could be remedied, any increase in the size of the area's livestock could not be translated into a rise in average income unless the commercial offtake could be raised.

[1] The Equatorial Nile Project, Being, the Report of the Jonglei Investigation Team By January or February drinking water would become short and the perennial grasses, previously burnt off to produce a green re-growth, are exhausted. At this point, the inhabitants would be forced to move towards the "*toich*" grazing lands. In the dry season the pasture in this area is Iush and plentiful. Water is also available in the riverine and areas adjacent to it (permanent, swamps) are their stay in the dry season. While they supplement their meager supplies of grain with milk, meat and fish from the pools and shallow water channels. As for the intermediate lands, they represent transitional areas where animals are kept and allowed to.

[2] Growth Employment and Equality: A comprehensive strategy for the sudan Report of the ILO/ UNDP Employment Mission 1975. ILO 1967.

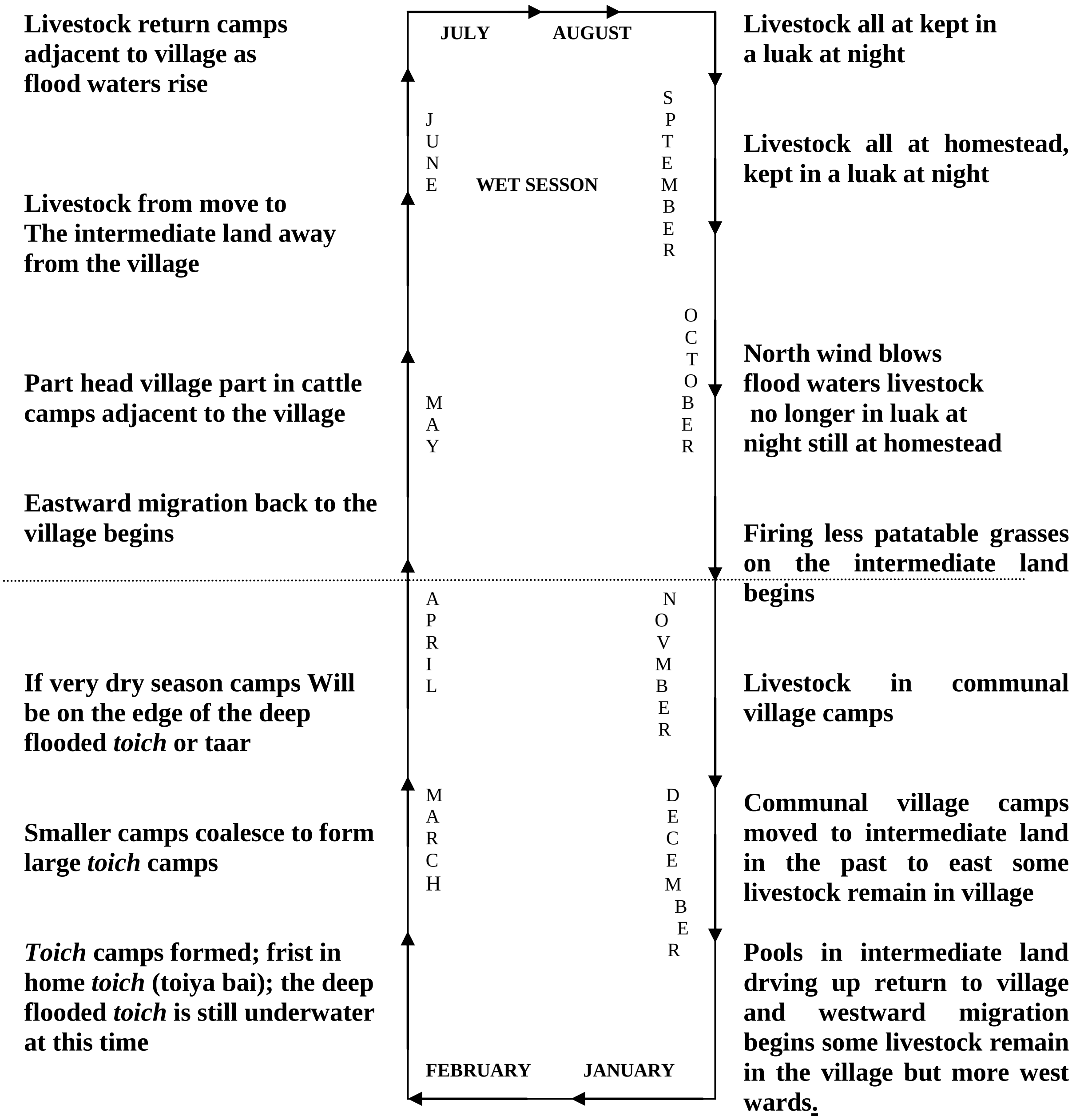


Fig.6.1: The typical migratory cycle of livestock owners in the flood plain region

This would require major investments in infrastructure and other services involving changes in physical environment. From a state of perilous equilibrium the area must move towards a dynamic modern economy however slowly.

6.3.2 Project impact

The canal, with its supplementary structures such as the parallel irrigation canal, the all weather canal bank road, navigation, irrigation schemes, and other community development projects would constitute a major economic activity. The impact of the canal on the project area would cover a wide range of socio – economic features of the region as follows:

a. Agriculture including crop production, livestock and fisheries.
b. Infrastructure including river and road transportation, markets and settlements.
c. Ecological improvements including insect and disease control.
d. Social and cultural.
e. Rural development.

Agriculture would be certainly the main beneficiary by virtue of its being the predominant sector in the current economy of the area. The canal would substantially increase both pasture and crop area. Significantly contribute to agricultural productivity and it would lead to a major rise in value of agricultural output. The canal would bring about these agriculture improvements through: (i) flood control and the maintenance of seasonal and annual fluctuations at the desired level, (ii) providing irrigation system, and (iii) Providing water supplies for human and animal drinking.

The flood control aspects would reduce the swamp area, increase riverine, *toich*, and intermediate land grazing and production capacities as well as improve its quality. The canal would provide protection against flood for the plains lying between its channel and Bahr El Zeraf. Further, by preventing “creeping floods" moving from the East and south towards the north, west, this would substantially increase the total area of flood free high and intermediate lands during the wet season. This would be particularly important in the light of the binding effect on livestock of the lack of grazing area during the wet season. Moreover, the controlling effect of the canal on “creeping floods" would greatly increase utilization of intermediate lands for both crop production and pasture. The Canal would also make the development of the area lying between the Canal and Bahr El Jebel possible. This area is estimated to amount to circa 3.7 million feddans and is suitable for both pasture and crop production. In fact, the irrigation main Canal which is designed to be built concurrently and parallel to the Jonglei Canal aims at irrigating 200.000 feddans in this plain. Lastly, the canal effects on increasing the utilized high intermediate land areas would reduce over cropping and overgrazing in the already utilized areas with substantial productivity benefits. It would also allow for greater utilization of *toich* which is currently under utilized due to the ceiling which the wet season production imposes on the size of livestock. Therefore, the Canal will provide a perennial source of water supply and consequently allow for use of the high and intermediate land all year round.

The construction of the canal will no doubt have its impact on the life of the inhabitants. One of the direct effects of the canal is that it will traverse the land inhabited by the thoi and Luaich Dinka living immediately south of River Sobat, as well as the Gwaeir Nuer and will form a physical barrier between each tribal group and one other of their receptive traditional land component types; high land, intermediate land, and *toich*, which provide the ecological base for their transhumant system. It is, therefore essential that crossing points be established across the canal in order that the cycle of migrations is not abruptly interrupted by canal. The canal will also act as a physical barrier to the lateral surface movement of water during the wet season, both for the run-off of water courses, which drain into the *toich* land and the creeping flow which runs across the intermediate land. Yet a third effect might be a reduction in the *tioch* and intermediate land, particularly in the southern Dinka land, and an interference with the established migration routes as a result of the withdrawal, from the present system, of large areas for the proposed agricultural development.

With regard to the transportation impact of the Canal, it would provide a new navigable route which shortens the distance between Malakal and Juba by 300 km. The Canal bank road would provide an all weather surface link with the north thus promoting local and inter- regional trade, improving the area transportation network, linking it with the rest of the country is a cornerstone for the future development of the economy of the area. The Canal would have a profound on the income and employment opportunities for the people of the region. The construction and operation of the canal and ancillary facilities directly generate employment opportunities for the local inhabitants. This should be welcome in the light of the stagnant economy of the area. However, the more important employment of the area, the more important employment effect of the Canal will be the indirect one. Expanding agriculture, its diversification intensification should generate much more income and employment. The increase sing employment opportunities in the area would stem the current emigration trend among the young people in particular. The Physical and economic changes in the area would have ramification on social and cultural values of the people. While social changes were not being entirely painless and universally welcome, the local population seems to be predisposed to accept change for the latter. The civil strife which broke out in 1955 between the northern and southern Sudan and the high disastrous floods between 1961and 1964, which forced a high proportion of young people to move outside the traditional sphere of life, are thought to have been the main instruments of change. Socio-economic surveys point out the inhabitants' dissatisfaction with their current environment, and their strong desire for change. Indications of change away from the traditional values and attitudes are noticeable in the wearing of clothes, acceptance of education for children, the use of vaccination to compact animal disease and the acceptance of modern medicine. New attitudes include the willingness to sell cattle and to equate cattle to money values were observed (Payne, 1976). In addition that the prospect of protection against floods and the implied security for their livestock wealth cannot be unwelcome to the local population despite initial adverse reactions invoked by most changes. The local population can certainly look forwards to better standards of living.

From the previous impact and different studies it was recommended that:

- The possibility of planning the canal alignment so that it will lie east of the Dinka and Nuer settlements should be studied
- The need for crossing and watering places along the canal should be studied
- On Nuer and Dinka land, the development of animal husbandry schemes, in addition to crop oriented agricultural development is recommended
- In Shilluk land agricultural development should be concentrated on crop production
- The topography of the Shilluk toiches downstream of the Sobat mouth should be studied and related to calculations of the future increase of the water levels of the White Nile there in order to forecast possible inundations of these toiches in the future.

CHAPTER 7. SUDD MARSHES MANAGEMENT TOOLS

7.1 Introduction

Wetlands resources and habitats have been extensively altered over years by commercial and residential developments. Understanding and predicting the impacts of these developments on wetlands resources need reliable mathematical model to simulate surface water movement in wetlands and slough channels along with realistic linkages between surface water and groundwater. This simulation is an essential process in the design of many projects constructed in or near wetlands. This chapter introduces the key knowledge for mathematical model which can be used for wetland management. Key knowledge for other tools such as decision support system is also discussed.

7.2 Mathematical Model

7.2.1 MIKE SHE model

MIKE SHE is one of the available commercial tools for distributed, integrated surface water/groundwater-modeling. MIKE SHE was developed 2003 by DHI Water and Environment (www.dhi.dk). It was originally developed as 'SHE' along with the British Institute of Hydrology and SOGREAH (France). In the 2003 version, all major hydrologic flow processes are dynamically coupled, including 2-D overland flow, 1-D channel flow, 3-D saturated zone flow, 1- D (Richard's based) unsaturated zone flow, snowmelt and evapotranspiration. Overland flow utilizes DEMs, while channel flow is simulated through the MIKE 11 code, which has extensive capabilities including, user-defined regulating structures, water quality and sediment transport, and a morphological module. It is also capable of simulating integrated advective-dispersive transport, sorption, biodegradation, geochemistry (including PHREEQC), and macropore flow, generally applicable for most hydrologic, water resources and contaminant transport applications. MIKE SHE utilizes rigorous physical flow equations for all major flow processes, but also permits more simplified descriptions. MKE SHE has undergone limited verification (http://www.integratedhydro.com/) to test its ability to simulate single component processes and some of their interactions. The model graphical interface is significantly improved in the 2003 version, offering a dynamic navigation tree, dynamic dialogs, and limited on-line documentation, and notably improved output animation capabilities. It seamlessly links with Arcview shape files and has well-organized spreadsheet-graphical functionality for ease in editing spatial and temporal input. MIKE SHE includes process models for all the parts of the land-phase of the hydrologic cycle, including:

- Precipitation, snowmelt and rainfall interception
- Vegetation-based evapo-transpiration,
- Overland sheet flow,
- Vertical unsaturated flow,
- Saturated groundwater flow, and
- Sewer and channel flow.

MIKE SHE is a modular modelling system that allows to mix-and match simple, lumped-parameter or water balance methods with advanced, physically based, finite-difference methods for each of the hydrologic processes. Each model process runs independently of one another and mutually exchanges water on a time step basis. Thus, it has the advantage of the temporal and spatial scales of the different processes and, in turn, solve problems across the full hydrologic spectrum - from detailed wetland studies to basin-wide water resource management studies. MIKE SHE is directly linked to both a channel flow module (MIKE 11) and a sewer flow module (MOUSE). MIKE 11 is used in applications ranging from simple routing of surface water to fully dynamic channel flow with dynamic flow control structures. MOUSE is used to study the steady-state to fully dynamic interaction between urban infrastructure networks and surface/subsurface hydrology. MIKE SHE's user interface is based on the conceptual model approach. The model data is specified (i.e. GIS data, gridded and time series data, and database data) independent of the numerical model grid and simulation period. At run time, the model independent data is processed and the numerical model is created and run for the specified simulation period.

7.3 MODFLOW model

As cited in Restrepo et al, 1998, the MODFLOW model is a two dimensional model can be used to simulate the impacts of commercial, industrial, and residential developments. The model enables the top layer of the grid system to contain overland flow and channel flow simulations. The wetland module can account for vegetation characteristics, simulation of surface flow routing, the export and import of water, and evapotranspiration. It can simulate the areal expansion and contraction of wetland system and the associated water routing (vertical and horizontal) in response to different hydrological conditions. Therefore, the wetland package coupled with MODFLOW can be used to simulate three dimensional sheet flows through dense vegetation and fluctuation of wetland water levels that may occur due to well field, ground water flow, and channel flow through a slough network, water diversions, precipitation, and evaporation. The model is also suitable for modeling the wetting and drying of the wetlands by combining vegetation and soil as part of the same layer. This approach allows the conservation equations to remain valid when the water surface falls below the soil surface.

The model can be used to determine the impacts of land use changes. Such impacts may include changes in water levels and the number of dry cells in wetland areas. In order to be applied properly, the model should first be used to analyze a project in the pre planning stage. Then the project should be monitored in the construction phase. Then the model should be reapplied at the project conclusion to assess changes in the system. The model limitation is the need to test the wetland model in areal field scenario. The model significant advantage is that a two dimensional approach which provides more practical basis to assess the impacts on a pre-acre basis.

7.4 Design of Decision Support Tool for Sustainable Development of SUDD Area

7.4.1 Background

A comprehensive water related information system of the SUDD region is the core for any sustainable development. The Sustainable development could include multi discipline projects in rural and urban areas such as irrigation, water supply and sanitation, navigation and transportation. Meanwhile, such system should consider global impacts like the Climate Change and human interventions such as Jonglei Canal, in national and transboundary dimensions.

7.4.2 Objectives

The main Objective of this part is to identify and describe the main features of the SUDD Decision Support System for sustainable development. Such system should be composed of several techniques such as database, GIS, remote sensing, and mathematical modeling. Different data should be available to implement, test and operate such sophisticated system. Therefore, this part will identify and describe the data needed for testing and operating the proposed DSS.

7.4.3 Brief Description of the System

The DSS of SUDD region consists of two main parts:

- Database and GIS represented on geographical platform that compromise of water resources economic, and social data sets, in addition to maps and remote sensing data.
- Analytical Planning tool to make tradeoff analysis between different alternatives of sustainable development in the area based on the major area of concerns. The area of concern can by identified through stakeholders participation, and decision makers consultation.

7.4.3.1 Key Question to be addressed by the System

The following questions are expected to be answered through the implementation process:

- What is the impact of the Climate Change on the Sustainable Development of the SUDD region in different Aspects?
- How much water can be conserved if the Jonglei canal project is completed, and without diverse impact on the SUDD wetland and community?
- What are the water resources management methods that can be used to minimize the negative impacts and maximize benefits from different development projects and the climate change?
- What would be the total changes in the inundation patterns of the Sudd wetland (spatial extent, depth, etc)?
- What are the estimated impacts on community livelihoods?
- What would be the approximate volume of water to be conserved to keep environmental and socio-economic impacts to acceptable limits, when applying transboundary projects?
- What are the different options for sustainable development under different human interventions and climate change scenarios?

7.4.3.2 Preconditions for System Development

a) Minimum required dataset are available (hydro-meteorological, Swamp extent and depth, environmental, socio-economic data, canal main features, land use and land cover maps, Soil maps, remote sensing data, etc..)

b) Agreed set of criteria and indicators to analyze the impacts (positive/negative) from the different developments alternatives.

7.4.3.3 Selected information products to be generated (Indicators)

The following set of information products will be generated for different climate change and human intervention scenarios (i.e. Global warming, Jonglei Canal, etc..)

- Volume of water conserved (total volume and time series);
- Total area reclaimed for agriculture;
- Hydropower generated;
- Special and temporal expansion of the navigation and transportation capacity;
- Extent of change in swamp area (permanent and seasonal) and its impacts on the livelihood of the community (decrease in livestock grazing area, fishery production etc.);
- Impacts on the flora and fauna that exist in the swamp;
- Total benefit from conserved water (by economic sectors, irrigation, hydropower, navigation);
- Expected development in tourists section.

7.4.3.4 Setting Up the Baseline Model

1. Setup a model for the base case (from Inlet to outlet of the swamp without canal), and without any climate change scenarios
2. Run water allocation and reservoir simulation models
3. Determine the water lost and outflow from the swamp
4. Verify the outputs of the model with real data.
5. Calibrate the model when necessary
6. Save the model

7.4.3.5 Analyze the consequences

A. Case of Human Intervention

The primary objective of the Jonglie canal Project was to conserve around 4.7 billion meter cube of water that is lost in the Sudd swamp mainly through evaporation and make it available for downstream use. The project was terminated in 1983 after completion of 260 km out of the total 360km. The Decision Makers in Nile Basin has realized the benefits of gaining additional water for various uses downstream and agreed to investigate the consequences, both positive and negative, that might occur due to the completion of the canal.

The following is the methodology that will be used to analyze the consequences:

1. Update the baseline model with completion of the Jonglie canal.
2. Run the model with the new setup for a few pre-set levels of water abstraction levels (levels of abstraction as input), for each level.

a. Determine the amount of water that can be conserved.
b. Determine the benefit gained from the water conserved for irrigation and hydropower locally and in downstream.
c. Determine area reclaimed for agriculture and its benefits
d. Use the user defined function to convert model outputs to selected (agreed) indicators (impact (loss) on livestock, fishery production, impact on flora and fauna)
e. Populate the MCA with indicator values for the current level of abstraction

3. Run the MCA tool under agreed set of criteria.
4. Select the "best" option

B. Case of Climate Change

c) Update the baseline model with different climate change scenarios.

d) Run the model with the new setup for different pre-set of rainfall patterns (inflow from Equatorial lakes, macro climate change on the area);

a. Determine the amount of water that can be conserved/ lost in the SUDD.
b. Determine decrease or increase for irrigation and hydropower locally and in downstream.
c. Determine area reclaimed for agriculture and its benefits
d. Use the user defined function to convert model outputs to selected (agreed) indicators (impact (loss) on livestock, fishery production, impact on flora and fauna)
e. Populate the MCA with indicator values for the current level of abstraction

3. Run the MCA tool under agreed set of criteria.
4. Select the "best" option

Use Cases

In the following we will represent some proposed use cases for the SUDD area Decision Support System

Table 7.1: proposed use cases for the SUDD area Decision Support System

Actor	Activity
Modeler & Decision maker	I Create and Configure Study
Hydrologist & GIS Specialist	II Data Preparation and Preprocessing for the Baseline Scenario 1. Prepare geo-spatial data using the GIS functionalities of the DSS A Import and quality assure any relevant spatial data (such as land use, land cover, soils) B Delineate hydrologic response units (HRU) using digital elevation models (DEM) C Determine relevant properties of HRUs through overlay of different spatial layers and through application of heuristic functions (e.g. soil hydraulic conductivity as a function of soil type and root zone depth) D Through analysis of remote sensing images (1) Determine spatial and temporal distribution of evapo-transpiration (2) Analyze extents of permanent and seasonal swamps (3) Determine river reaches and their properties (and in addition using DEMs and data sets from studies and reports) 2. Prepare input time series for daily and monthly time steps A Import historic time series (such as rainfall, flow, temperature) B Quality assure time series (e.g. through gap-filling)
Modeler	III Model Configuration for the Baseline Scenario 1. Set-up model A Set-up and configure semi-distributed rainfall-runoff models for specific parts of the sub-basin (1) Discretize system according to the HRUs as defined in previous steps (2) Link hydro-objects to each other (set-up topology) and define types of linkages (e.g. reaches) (3) Link input time series (e.g. rainfall and evaporation) to specific hydro-objects B Set-up conceptual water-spine model for the wetlands (1) Model permanent and seasonal swamps as shallow

Actor	Activity
	lakes (2) Define evapo-transpiration (ET) and seepage properties of swamps (3) Link swamps to each other and with reaches and define flow properties and rules (e.g. using threshold functions – as necessary use scripting to define specific functional relationships) (4) Define conceptual GW hydro-objects and link these to the shallow lakes and the reaches (through their seepage properties) (5) Link input time series (e.g. rainfall and evaporation) to specific hydro-objects (6) Define virtual nodes to aggregate “losses” (ET & seepage) from swamps and link these to selected hydro-objects C Link the sub-models (1) Check the sub-models in the DSS GUI (2) Link selected hydro-objects in the rainfall-runoff models with selected hydro-objects in water-spine model to define flow/linkage between the models – for automatic data exchange between the sub-models (3) Define the modeling sequence of the sub-models (rainfall-runoff and water spine models) 2. Calibrate and validate each sub-model A Experiment with different (1) evapo-transpiration approaches/methods (2) routing functions in reaches B Analyze sensitivity of results with regard to different input data - such as (1) evapo-transpiration methods (2) resolution and topology of schematic (3) Change parameterization and topology as necessary (re-setup model) and test the model(s) iteratively
System	3. Simulate for baseline scenario; run set of models (model tools will automatically execute according to user-defined sequences and model linkages)
Modeler	IV Scenario Configuration and Run for Jonglei Canal
	1. Copy and modify water spine model of baseline scenario and define different sets of parameters for inlet node of Jonglei Canal, such as: A Water abstraction rules for flows (e.g. as diversion flow as a function of another state variable of another hydro-

Actor	Activity
	object) B Water abstraction flows/levels (e.g. as time series)
	2. Set-up and configure hydraulic model of Jonglei-Canal; use DEM and other data sets to determine cross-sections and longitudinal profile
	3. For each set of parameters define a scenario and link the set of models (rainfall-runoff and water spine) with the hydraulic model of Jonglei Canal (including definition of modeling sequence) – new linkage between water spine and hydraulic model through inlet and outlet node of Jonglei Canal
System	4. Simulate each Jonglei-Canal scenario; run set of models (according to defined modeling sequences)
Modeler	V Scenario Configuration and Run for Climate Change
	1. Copy and modify water spine model of baseline scenario and define different sets of parameters for inlet node to SUDD area, such as: A Increase or decrease in the inflow from Equatorial Lakes Region B Local increase or decrease in rainfall patterns
	2. Set-up and configure hydraulic model of the SUDD region; use Tank Model or other models to determine lose or gain in the wetlands area
	3. For each set of parameters define a scenario and link the set of models (rainfall-runoff and water spine) with the hydraulic model of SUDD (including definition of modeling sequence) – new linkage between water spine and hydraulic model through inlet and outlet node of SUDD region
System	4. Simulate each Climate Change scenario; run set of models (according to defined modeling sequences)
Modeler & Decision Maker	VI Indicator Definition (and Calculation)
	1. Review all information that was made available through the data preprocessing phase using the DSS GUI
	2. Define relevant indicators for scenario comparison and MCA, such as A Total area reclaimed for agriculture B Extent of change in swamp area (permanent and seasonal) and its impacts on the livelihood of the community (such as decrease in livestock, grazing area, fishery production) C Impacts on the flora and fauna that exist in the swamp D Total benefit from conserved water (in this case through assessment in other use cases of the DSS)

Actor	Activity
	3. Define relationships between model data/properties and the above indicators A Import and/or edit tables that represent relationships (in this case these relationships are derived outside the scope of the DSS) B Write scripts to formulate functional relationships and/or aggregations as appropriate
System	4. Calculate indicators for all scenarios including baseline scenario (convert model outputs to indicators as defined in indicator definition phase) 5. Populate MCA with indicators as specified and defined in the indicator definition phase
Modeler & Decision Maker	VII Scenario Analyses
	1. Compare for each Jonglei-Canal and climate change scenario results with each other and with results of baseline scenario: Examples for criteria to be compared are: A Extents of wetlands (including surface areas, water volumes, water elevation) – maxima and minima B Evapo-transpiration (average yearly values, temporal distribution, minima, maxima and other aggregated values) C Outflows from the Sudd (average yearly values, temporal distribution, minima, maxima and other aggregated values) All the indicators that were determined in the indicator definition (and calculation) section
Decision Maker	VIII MCA
	1. Run MCA tool for the criteria used in the scenario analyses Select the “best” option

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GIS Based Decision Support Tool for Sustainable Development of SUDD Marshes Region (SUDAN)

The Sudd Marshes wetland is one of Africa's largest tropical wetlands (30,000-40,000 km2) 5,700,000 hectares, (7o 34\ N 030o39\ E) located in Southern Sudan in the lower of Bahr el Jebel (White Nile). The Sudd formed from the spillage of Nile water. The wetland supports a diversity of ecosystems with a rich flora and funa. The swamps consist of wide blankets of high vegetation: papyrus, reeds, elephant grass, etc., which extend from the river bed to the dry ground on either side, interrupted only by lagoons and side channels. To the west of the Sudd there are the smaller wetlands of the central Baher el Ghazal Basin, and in the east is the Machar marshes of the Sobat River.

Wetland development research (conservations, resource utilization, etc.) require an accurate knowledge of the water balance components over the wetland: precipitation, evaporation, inflow, outflow and interaction with groundwater. Similarly, evaporation and biophysical characteristics of the wetland are required to better understand its interaction and feedback with the atmosphere. Usually evaporation from a wetland is a major component of its water budget, though complex to determine (Linacre et al., 1970). This research is considered an initiative attempt to explore the potential entities can be used for Sudd marshes wetland development. This study is supported by the Nile Basin Capacity Building network for River Engineering. The study aims at developing some recommendation for wise use of Sudd wetlands for poverty reduction, improving livelihood and conservation of the biodiversity of the ecosystem.

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