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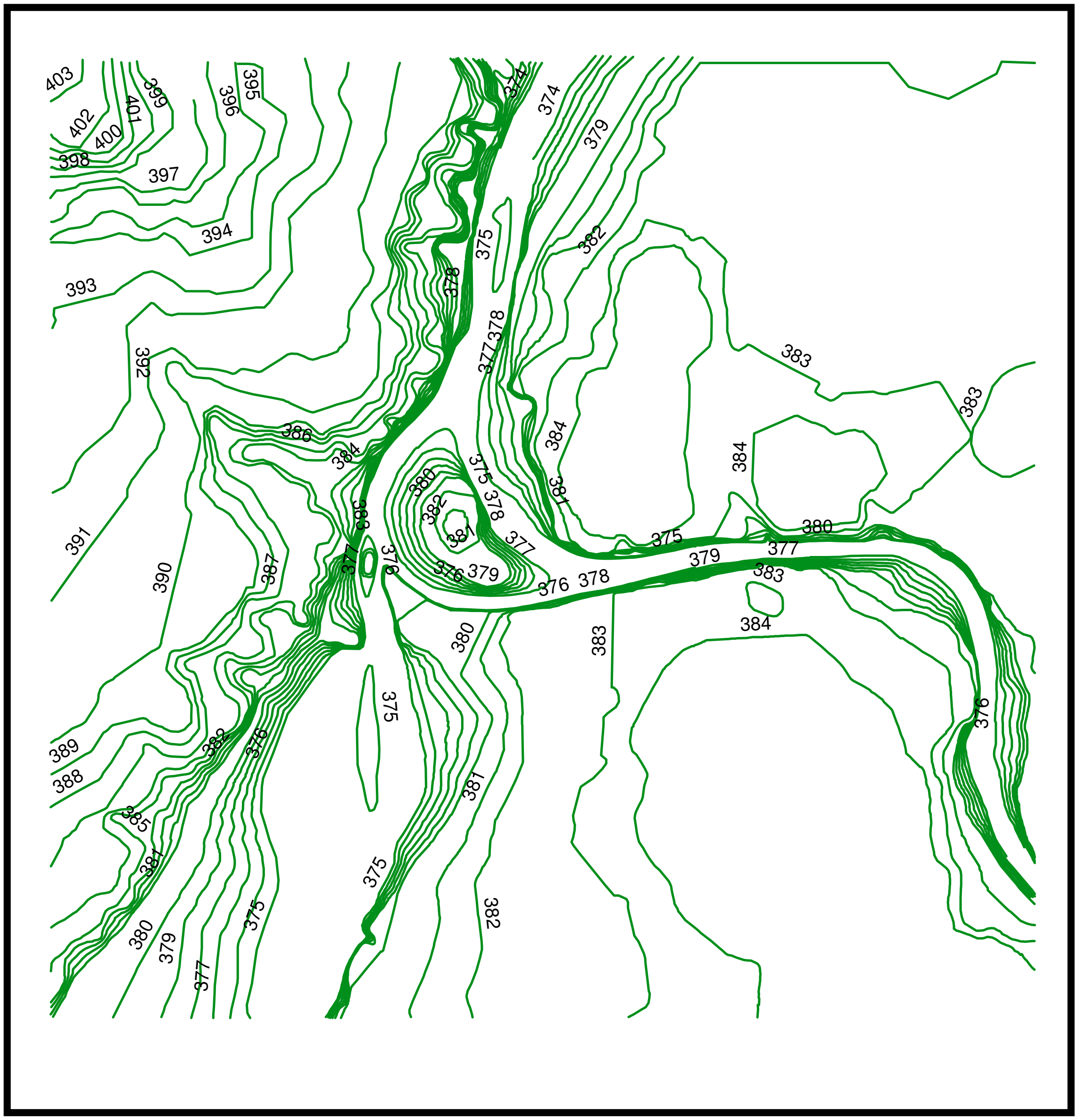

Flood Analysis in the Blue Nile, a Case Study of Flood Simulation in Khartoum with Climate Change Scenarios

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Flood Analysis in the Blue Nile, a Case Study of Flood Simulation in Khartoum with Climate Change Scenarios

Master of Science Thesis
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April 2008

Dedication

This research is dedicated to my parents, whose vision, wisdom and constructive criticism over the years have contributed so much to my personality. I dedicate this work also to my wife Elham; I am deeply and forever indebted to her for her love, support and encouragement through the research. I dedicate this work also to my lovely daughter Doaa.

Abstract

Flood is one of the major issues which effects many people in different levels in Sudan. The decision makers need new techniques to support their decision before and during the flood. The Water Resources Planning and Management Project (WRPM) of NBI funded this research for capacity building in the field of DSS in Hydroinformatics at UNESCO-IHE.

From July to September 2007, Sudan suffered from the most destructive flood, Sudan has faced in the last 20 years. Many cities and especially Khartoum (the capital of Sudan) suffer regularly from flooding. The damage of flood in 2007 in Khartoum was more than 45 million US dollars.

The Blue Nile contributes with around 68%, Sobat with 16% and White Nile and Bahar-El-jabal with 16% of the flow in the Main Nile after Khartoum. There is an urgent need nowadays for better understanding of flood generation. Moreover, it is crucial to have a simulation model which can understand the relationship between the discharge at the border of Khartoum and its contribution to the flood, in order to save the life of the people and save animals and goods.

The World Bank funded Delft Hydraulics to build a real time forecasting model after the devastating flood in 1988. The model started working in 1992. Unfortunately, nowadays the model -Flood Early Warning System (FEWS) - suffers from many problems, for example with respect to forecasting the time of the flooding.

This research contains preparatory analyses for improvement of the flood forecasting model, and an analysis of the current and potential flooding problems in Khartoum. A water balance between Rossieres (500 km from Khartoum) and Sinnar (340 km from Khartoum) and between Sinnar and Khartoum has been made in order to know if the available data is sufficient and accurate to build a 1D hydro-dynamic model, to be used to predict the discharge and water levels at Khartoum during the flood season. From the results of the water balance between Rossieres and Sinnar dam, it can be concluded that the available data is of good quality and is probably sufficient to build a 1D hydrodynamic model. Water balance for the reach Sinnar and Khartoum showed best results. From the results of the water balance between Sinnar and Khartoum dam it can be found that the data is of good quality for building a 1D hydro-dynamic model.

For flood analysis a 2D model which simulates the water level at Khartoum has been made. SOBEK 2D was used, to simulate the water depth at Khartoum. A flood extent map for Khartoum was made with GIS. A topographical map of Khartoum was used for better understanding of the flood extension and depth. A comparison between the free SRTM Digital Elevation Map and the elevation contour map has been made. The differences between the elevation map from a free source and the topographical elevation map were large. The elevation differences in some areas along the river bank are 17 meters. SRTM free source for DEM map is not recommended to be used for the extension of the flood in Khartoum. The result of the extent of the flood from SOBEK had been checked with free remote sensing images. The result of the flood extension from SOBEK compared with the remote sensing images was almost the same in extent. Different scenarios were computed to simulate future expected flood due to climate change.

Omdurman was almost unaffected from flood by climate change, and Bahri was more affected from flood due to climate change and Khartoum was highly affected by the climate change.

The flood extent map will provide the decision makers with information of areas at risk by defining flood risk zones. Moreover, it will help spatial planning, and public awareness to be raised in the areas at risk of flooding.

All the steps and sources of information have been put in a base data file for future research.

Keywords:
Simulation, flood, Blue Nile, Khartoum, SOBEK, 2D, GIS, Remote Sensing, flood extent, DEM, scenarios, Climate change

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I would like to express my deep and sincere gratitude to my supervisor, Prof. D.P. Solomatine, PhD, MSc, Head Core of Hydroinformatics department. His wide knowledge and his logical way of thinking have been of great value for me.
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Finally, I would like to thank everybody who has been important to the successful realization of thesis, as well as expressing my apology that I could not mention personally one by one.

Modathir Abdalla Hassan Zaroug, 8 of April 2008.

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List of abbreviations

ASCII	American Standard Code for Information Interchange
C	Chezy coefficient
CCC	Canadian Center for Climate
DEM	Digital Elevation Model
Delft-FLS	Delft Flooding System
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
FEWS	Flood Early Warning System
GFDL	Geophysical Fluid Dynamics Laboratory
GFDLT	Geophysical Fluid Dynamics Laboratory Transient
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies
HRS	Hydraulics Research Station
HAC	Humanitarian Aid Commission
IHE	International Institute for Infrastructure, Hydraulic and Environmental Engineering
IPCC	Intergovernmental Panel on Climate Change
MISR	Multi-angle Imaging SpectroRadiometer
MPI	Max Plank Institute
NBI	Nile Basin Initiative
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
TIN	Triangular Irregular Networks
UKMO	United Kingdom Meteorological Office
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNITR	United Nations Institute for Training and Research
UNOSAT	Operational Satellite Applications Programme
1D	One Dimensional
2D	Two Dimensional

1 Introduction

1.1 Introduction

From July to September 2007, Sudan suffered from the most destructive flood the country has faced in the last 20 years. Many villages and towns in the whole country were inundated. The floods affected the lives of thousands of people and animals. The flood was accompanied by pollution of water and spread of insects that are a threat to the public health. Infectious diseases appeared in many places threatening the life of many inhabitants. Therefore, there is a need to mitigate the consequences of flooding, especially in the capital Khartoum.

1.2 Background Information

Sudan lies in tropical Africa (Figure 1.1). Its climate varies from equatorial in the south, savannah in the middle lands, and continental in the north and Mediterranean climate with winter rain in the east. The rainy season extends roughly from June to September. The annual rainfall is 1800 mm, though at Khartoum the capital it is only 80 mm. Sudan is generally spreading a wide plain, with mountains in the north east, near the red sea coast and near the south east borders. The Nile is the dominant geographical feature of Sudan as around 70% of the area of the country is situated with in the Nile River catchment. Severe floods occurred in recent years in Khartoum: in 1999, 2000, 2001, 2006 and 2007.
The Blue Nile drains a large area of the Ethiopian highlands and is the largest tributary of the Nile River, providing a vital source of fresh water to Sudan. The Blue Nile contributes with around 68%, Sobat with 16% and White Nile and Bahar-El-jabal with 16% of the flow in the Main Nile after Khartoum.

1.3 Problem description

The damage resulting from the 2007 flood in Khartoum State alone was estimated by more than 45 million US dollars (Ministry of Civil Defence, 2007). There is a great demand to reduce such losses in future flood situation.
The current operational flood forecasting and early warning system -Flood Early Warning System (FEWS, Delft Hydraulics 1992) - suffers from many problems, for example with respect to forecasting the time of the flooding.
In order to describe the problem of flooding in Sudan, and especially in the Blue Nile in Khartoum, we need to know damage statistics in Sudan and in Khartoum. There is no specific report about damages in Khartoum except in 2007. The records of some years are missing. Either the damages are small or the reporting is not done or the report is not saved and documented well.
The people along the White Nile in Khartoum are the people who suffer regularly from flood (Figure 1.1). The Blue Nile during the rainy season in the upper catchment in Ethiopia brings with it a lot of sediments. The flow of the Blue Nile is higher than the flow of the White Nile. The White Nile brings little sediment. During the wet

season, from July to September the high flow in the Blue Nile blocks the water from the White Nile, and the resulting back-water causes flooding of the White Nile banks.

Figure 1.1: Sudan map

Elduma, (2004) summarized the flood disasters in Sudan from 1965 to 2004 are as shown in Table 1.1. From Table 1.1, it follows that on average every 2 or 3 years there is a flood.

Table 1.1: Flood disaster in Sudan and impact on people (Elduma, 2004)

Events	No. of event	Killed	Injured	Affected
Flood	17	383	18,556	6,614,962

In his report also we can read that the majority of population is around the Blue Nile and White Nile. When the flood hit those highly populated areas, the damage become high. The population density in Sudan (inhab/km^2) is shown in Figure 1.2. Figure1.3 shows the inundated people and animals during the flood.

This research is intended to contribute to better management of future floods in order to reduce flood damage and the number of people affected.

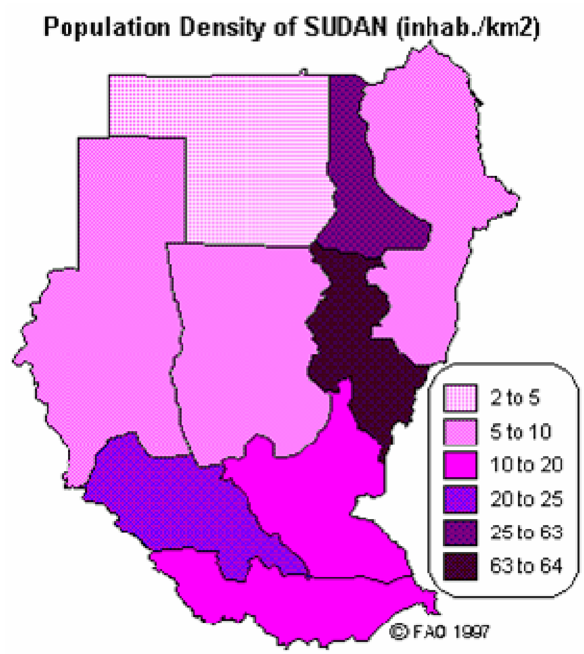

Figure 1.2: Population density in Sudan.

Figure 1.3: Inundated area, affecting people, animals and goods

1.4 Literature review

1.4.1 Data reliability and availability

Mekawi et al., (2005) in her research made discharge and water level validation from (1965-2000).

She found that the availability of the data for the period 1965 to 2000 is estimated around 90%. In addition, the work shows that the greater part of the available data can be considered reliable, accurate and in agreement with other well known sources. This is, no doubt, promising for future work. However, the fact that the data of specific years at some of the gauging sites is uncertain should not be avoided.

1.4.2 Flood forecasting in the Blue Nile

Conway, (1997) in a paper of a water balance model of the Upper Blue Nile in Ethiopia, showed that no published data existed for the whole of the Blue Nile in Ethiopia until the USBR carried out a major survey of the land and water resources of the Blue Nile basin between 1958 and 1963 (USBR, 1964a,b,c). More recently, Sutcliffe et al. (1989) and Dugdale et al. (1991) describe flood forecasting work on the Blue Nile using METEOSAT-derived rainfall estimates and a simple daily hydrological model.

The World Bank has funded flood forecasting work on the Blue Nile undertaken by Delft Hydraulics, in association with the Soutanes Water Resources Department (Grimes et al, 1993; El Amin El Nur et al, 1993). An 11 region distributed model of the Blue Nile was developed, based on the Sacramento Watershed model (Grijsen et al, 1992). The name of this model is FEWS. Sudan Flood Early Warning System (FEWS) is in operation since August 1992, providing an advanced operational tool that gives three days a head the water levels and flows at El Deim, using remote sensing and hydrologic modelling techniques. However there is a new version of FEWS which is not yet available in Sudan. Moreover, the old version of FEWS which is used in Sudan encounters many problems nowadays like:

- The bathymetric survey has been done in 1991 to support the development of the FEWS model. Two bathymetric surveys have been done after that and none of them included in FEWS model.
- The capacity of Roseris Dam and Sinnar Dam were changed because of the great amount of sediment that comes from the upper catchment during the flood.
- Dams' operation rules were never updated to the model since the development of the model in 1991.
- New dams were not included to the model.
- The most important input after the development of the model is the satellite data of Tamsat. However, there is no any access to the Tamsat data nowadays. For the model just some images from private source have been used, which do not fit the model well.

As a result there is need for a new model to predict the flood especially in Khartoum.

1.4.3 Presentation of the flood and its effect

Alphen, (2007) who works for the Dutch Ministry of Infrastructure and Water Resources, mentioned in a presentation about Risk Management Cycle and Flood Risk Mapping, different ways for presenting maps. For Example, he made maps combining growth of population and economy, potential flood extent, flood extent, depth of flooding, scenario's for max. flood depth, flow velocities, scenario's for progress and rate of rise, flood risk as combination of intensity (depth and or velocity) (or sensitivity) and probability, potential damage and casualties, flood risk map for insurance, risk of vital objects, social vulnerability, evacuation maps and evacuation routes.

Abdallah, (2005) mentioned in his report about Flood Risk Management that there are three components that determine flood risk, for example, flood hazard, vulnerability and exposure:

- Hazard: the threatening natural event including its probability / magnitude of occurrence.
- Vulnerability: the lack (or loose) of resistance to damaging/destructive forces.
- Exposure: the values/humans that are present at the location involved.

He mentions the development of flood risk management by the following elements: prevention, protection, preparedness, emergency response and recovery and lessons learned.

1.4.4 Flood damages in Sudan

SUTCLIFFE, (1989) this paper showed that it is important to note that two distinct events occurred in succession: an exceptionally intense storm over Khartoum, and heavy rainfall over Atbara basin (and to a lesser extent the Blue Nile basin) which gave rise to inundation in north Sudan.

Humanitarian_Aid_Commission, (2007) showed that the most affected areas in Khartoum are: Sherg Al Nile, Jabl Awlia, Omdurman, Mayo, Al Hella Al Gadeida, Soba, Umdwanban, and Al Elafon. Moreover, they recommended Toti Island and residential areas around both Blue Nile and White Nile must take a preventive action to save lives and properties.

1.4.5 SOBEK 1D/2D model

Bashar, (2005) in his Msc. thesis did research on Floodplain Modelling in Bangladesh by SOBEK 1D/2D Coupling System. He mentioned Delft-FLS as a reliable model for simulation of the flood, which is now embedded into SOBEK as Overland Flow Module, is a two dimensional hydrodynamic simulation package based on fully 2D shallow water equations. Moreover, he mentioned the Coupling of 1D and 2D Model as an implicit coupling of 1D and 2D schematisations is based on the concept that both are defined on separate computational layers, similar to the concept of the storage of spatial data on different layers in a GIS. (Figure 1.4) shows the combined finite mass volume for 1D/2D computations.

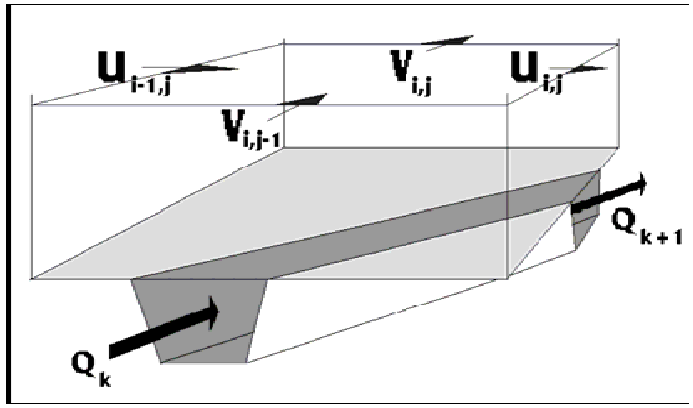

Figure 1.4 combined finite mass volume for 1D/2D computations (source: adopted from Bashar, 2005).

Fei, (2004) in his Msc. thesis did research on Modelling Compound Channels with SOBEK, he mentioned both the 1D2D coupling model and the fully 2D model can reproduce the data following the trend of small scale laboratory data, and the model shows good fitting with laboratory data. Moreover, the boundary condition is the key issue during the model set up. Further more, he found for different Manning roughness coefficient of 2D grid, the model was not sensitive enough to represent the roughness changes.

SOBEK is an integrated software package for river, urban or rural management. This program is very easy to understand it and quick to know it. It can download information from a variety of standard data formats and GIS systems. (Delft-Hydraulics, 2006).
The Overland Flow (2D) module of SOBEK-Rural is designed to calculate two-dimensional flooding scenarios. The module is fully integrated with the 1DFLOW module for accurate flooding simulation. It is especially designed to simulate dam breaks and dike breaks. The hydrodynamic simulation engine underneath is based upon the complete Saint Venant Equations. It can simulate steep fronts, wetting and drying processes and sub critical and supercritical.
The water flow is computed by solving the complete De Saint Venant equations.
The flow in one dimension is described by two equations momentum equation and the continuity equation. (Delft-Hydraulics, 2006)

Equations used for SOBEK 1D:

The continuity equation reads:

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

Where:
A_f = Wetted area
q_{lat} = Lateral discharge per unit length (m^2/s).
Q = discharge (m^3/s).
t = time (s).
x = distance (m).

The momentum equation is:

$$\frac{dQ}{dt}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right)+g*A_f*\frac{\partial h}{\partial x}+\frac{g*Q*|Q|}{C^2*R*A_f}-W_f\frac{\tau_{wi}}{\rho_w}=0$$

The first term describes the inertia.
The second term describes the convection.
The third term describes the water level gradient.
The fourth term describes the bed friction.
The fifth term describes the wind friction.

Q= Discharge [m3/s].
t= Time [s].
x= Distance [m].
A_f= Wetted area [m2].
G= Gravity acceleration [m/s2] (=9.81).
h= Water level [m] (with respect to the reference level).
C= Chézy coefficient [m½/s].
R= Hydraulic radius [m].
W_f= Flow width [m].
t_{wi}= Wind shear stress [N/m2].
r_w= Water density [kg/m3]. (1000).

Equations used in SOBEK 2D:

The flow in two dimensions is described by three equations: the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction.

The continuity equation

$$\frac{\partial \varsigma}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{dy}=0$$

Momentum equations 2D flow

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \varsigma}{\partial x}+g\frac{u|V|}{C^2h}+au|u|=0$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \varsigma}{\partial y}+g\frac{v|V|}{C^2h}+av|v|=0$$

Where:
u: velocity in x-direction(m/s)
v: velocity in y-direction (m/s)
V: velocity: $V=\sqrt{u^2+v^2}$
ς: Water level above plane of reference (m)
h: total water depth: ς+d(m)
d: depth below plane of reference (m)
C: Chezy coefficient $(m/s)^{1/2}$

a: wall friction coefficient (1/m)

The continuity equation ensures the conservation of fluid. They consist of acceleration terms, the horizontal pressure gradient terms, advective terms, bottom friction terms and wall friction terms. These equations are non-linear and they are a subset of the well-known shallow water equations that describe water motion for which vertical accelerations are small compared to horizontal accelerations (this applies to tidal flow, river flow, and flood flow).

1.4.6 Climate change and its effect for future flooding in Khartoum

Boko et al., (2007) in the IPCC report about Africa, they mentioned that Africa is one of the most vulnerable continents to climate change and climate variability. In addition, Rainfall is likely to increase in some parts of East Africa, according to some projections, resulting in various hydrological outcomes. (Fig1.5).

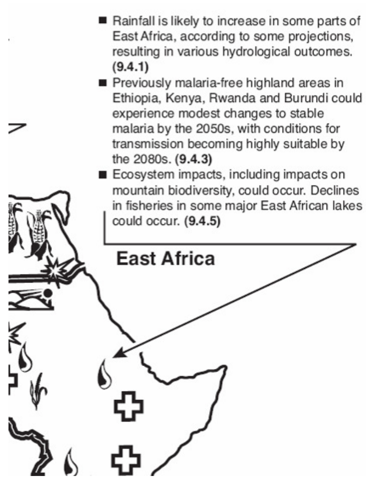

Figure 1.5 possible future impacts and vulnerabilities associated with climate variability and climate change for Africa (Boko et al., 2007).

Christensen et al., (2007) expected that there is likely to be an increase in annual mean rainfall in East Africa. It is unclear how rainfall in the Sahel, the Guinean Coast and the southern Sahara will evolve.

Young, (2004) assessed how climate change will impact the engineering design of the Merowe dam. She mentioned that the evapotraspiration lead to precipitation, as a consequence lead to high flow of the Nile. From the extensive literature review, she found that, there is a wide disparity in predictions of future Nile flow scenarios. Strzepek et al., (1995) found changes in runoff from a hydrological model using GCM based climate change scenarios for doubled global atmospheric concentrations (2xCO_2) provide widely diverging pictures of possible future Nile flows: GISS—a 30% increase; UKMO—a 12% decrease; and GFDL—a 78% decrease. These are postulated for the year 2060. (Conway and Hulme 1996) suggests currently anticipated changes in atmospheric concentrations of CO_2 by year 2025 would lead to air temperature increase of 1°C across Nile Basin, leading to increased evaporation loss and slight increase (2%) in rainfall in Blue Nile Basin and slightly larger increase (5%) over Equatorial Lakes region, spread fairly evenly through wet and dry seasons.

(Yates 1998a) found that Nile water resources declined under GFDL and increased for the GISSA and UKMO scenarios. (Yates 1998b) supports previous findings that changes in precipitation and to a lesser extent temperature over the Nile basin could have serious consequences on regional water resources throughout this large African basin. The 2xCO2 GCM scenarios gave a wide range of changes both in total water yield at Aswan and regional hydrologic changes throughout the basin. Five of six GCMs showed increased flows at Aswan, with increases as much as 137% (UKMO). Only one GCM (GFDLT) showed a decline in annual discharge at Aswan (-15%). Five of six GCMs predict increased precipitation in equatorial Africa. With some GCM scenarios predicting large increases in Nile discharge, there will be a need to increase flood protection, particularly in the Sudan.
The author at the end estimated 6% of the Nile increase at Aswan Dam.

Kim, (2007)expected that in a 100-year time series analysis using the outcomes of the six general circulation models showed that precipitation changes for the 2050s (2040 through 2069) can be -7% to 28% with a mean increase of about 11%.

Yimer, (2008) who is a NBI student works in parallel research; he provided input for this research. He expected an increase inflow during the rainy period, in August he expected and increase of 15%.

It can be concluded that here the majority of the models expected an increase in the Nile flow, but it's difficult to determine an exact number of an increase. There is a high uncertainty about the climate change in the Blue Nile due to different model that had been used to predict the rainfall. So, different scenarios for climate change should be made.

1.4.7 Water Balance in Blue Nile

Abbas et al., 1999) in the research of Water Balance of Roseires | Sennar Reach, found that the annually water balance between Rossieres and Sinnar showed a good result. In addition, the abstraction project between Rossieres and Sinnar consumes around 6% from of the annual river flow, this percent in some creases up to 100% during the low flow of the river. Moreover, he calculated the catchment of the rainfall between Rossieres and Sinnar Dam, the catchment produces around 1.5% of the river flow, and it can be up to 10% to 15 % on daily basis.

For the calculation of rainfall runoff for the catchment between Rossieres and Sinnar, five rain stations have been used for the calculation of the runoff. The reach has been divided to three sub-catchments as shown in Table 1.2. The runoff coefficient has been estimated for the three sub-catchments as shown in Table 1.3.

Table 1.2: Sub--catchments between Rossieres and Sinnar.

Sub-catchment	North	Middle	South
Area in Km^2	2268	10205	2194
Rain gauges	Sinnar, Um Benen	Um Benen, Abu Naama, Damazine	Damazine, Bau

Table 1.3: Runoff coefficients.

Catchment	North	Middle	South
April to June	0.08	0.1	0.12
July	0.1	0.12	0.14
August to Sep.	0.14	0.18	0.28
Oct. to Dec	0.09	0.11	0.13

1.5 Objectives

1.5.1 Main objective

The main objective is to analyse and simulate the flood in Khartoum for the Blue Nile in Sudan and prepare a GIS map for the expected flood areas in Khartoum, and to help decision makers to take mitigation measures.

1.5.2 Detailed objectives

The detailed objectives for this research are:

- Literature review.
- Data collection from Sudan.
- Data collection from free web sites.
- Data processing and validation of the data.
- Flood analysis on the basis of the data. What are the causes of flooding? What is the role of local rainfall? What are the thresholds of discharge and water level in the Blue Nile at Khartoum at which flooding may occur?
- Make water balance for the Blue Nile.
- Preparation of detailed topographical elevation map for Khartoum city.
- Comparison between the detailed topographical elevation map and the free source elevation map from SRTM website.
- Preparation of 2D hydrodynamic model, which simulates the water level in the Blue Nile and White Nile.
- Preparation of flood depth map and flood extent map in Khartoum.
- Comparison of modelled flood extent in Khartoum with remote sensing images.
- Generate different scenarios for expected climate change.
- Document the steps of the work and the collected data and reports

1.6 Methodology

The methodology which is followed in this research is:

- A water balance along the Blue Nile will be made to check the data and the system.
- A GIS tool will be used to create a detailed elevation topographical map for Khartoum by digitizing contour lines for Khartoum city and lower the river by using the historic cross sections of the rivers.
- A free source site for DEM map will be used, and Arc Hydro Tools will be used to give the river its elevations.
- The 2D model (SOBEK) will be built for Khartoum to simulate the water depth and the extent of flood in Khartoum.
- The generated water depth in Khartoum from SOBEK software will be extracted as an ASCII file, and then GIS will be used to present the flood extent map and flood depth.
- The result of flood extent from SOBEK and free sources of remote sensing image at the high period of flood will compared.
- Different scenarios would be generated for expected flood due to climate change or due to any extreme event such as heavy rainfall in the upper catchment combined with heavy local rainfall.

1.7 Tools

In this research SOBEK will be used, because the new version of FEWS Sudan will use SOBEK. Moreover, it is a powerful instrument for flood simulation and flood forecasting, The GIS will be used because it is a good tool in presenting and overlaying different features. Arc Hydro Tools will be used to lower the river. Remote Sensing will be used because it shows the flood extent in different years before and after the flood.

2 Data

In this chapter a description to stations will be made. Moreover, the collected data from Sudan and free sources will be described and analysed.

2.1 Introduction

Figure 2.1 shows the Blue Nile and its tributaries and the White Nile. Moreover, it shows the location of the stations and the location of the dams. Table 2.1 shows the longitude and latitude for different stations.

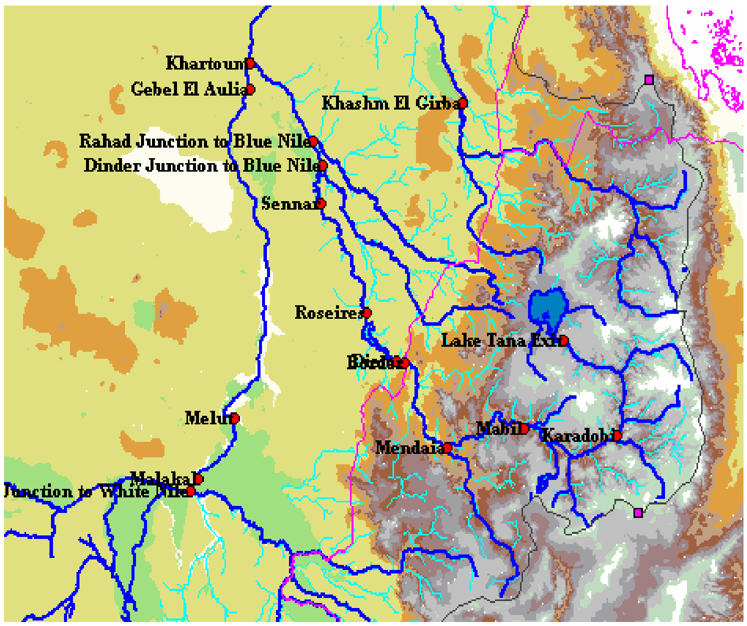

Figure 2.1 Blue Nile map (from Nile DST software)

Table 2.1 The longitude and latitude of the stations

Station name	Longitude	Latitude
Tamaniat	32.65	15.96667
Khartoum	32.51667	15.6
Jabal Awliya	32.5	15.21667
Medani	33.51667	14.4
Sinnar Dam	33.63333	13.55
Gazira & Managil	33.63333	13.55
Hawata	34.61667	13.4
Giwasi	34.1	13.31667
Rossieres Dam	34.38333	11.95
Eddiem	34.98333	11.23333

2.2 Measurement stations

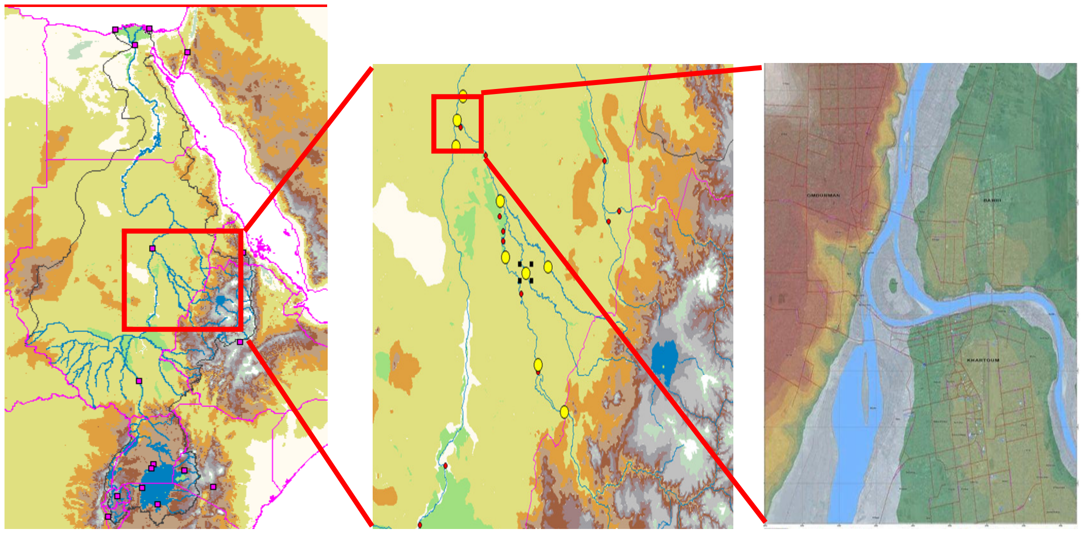

Figure 2.2: Down scaling to the study area

The Blue Nile system:
The Blue Nile system consist from some measuring stations, two measuring tributaries and abstraction projects

Eddiem Station:
It's located at the border of Ethiopia and Sudan. It's very important station, because the operation of Sinnar and Rossieres depend on it. It measures the discharge to the Blue Nile at the border. It's located at deep rock area which gives good records.

Rossieres Dam Station:
There is an upstream gauge reading, downstream gauge reading and discharge measurement. The discharge is the summation of the discharge from the deep sluices, spill way and hydropower station. The upstream gauge is reliable. The downstream gauge is subjected to the turbulence of the flow, and it's located on Rossieres bridge pillar, and there is a possibility of an error up to 30cm. Abbas et al, (1999). Figure 2.3 shows Rossieres Dam during the data collection period.

Figure 2.3: Rossieres dam with the deep sluices and spell way closed (Zaroug, 2008)

Sinnar Dam Station:
There is an upstream gauge reading, downstream gauge reading and discharge measurement. The upstream and downstream gauges are considered reliable, because the downstream gauge is located at 1.4 km from the dam. Fig2.4 shows Sinnar Dam during the flood season.

Figure 2.4: Sinnar Dam with opens gates during the flood season.

Medani Station:
For Medani station there is only gauge station, and there is no discharge measurement. An equation which describes the relation between the water level and discharge should be made in the future.

Khartoum Station:
There is a gauge station on the Blue Nile and there is also discharge measurement for the Blue Nile at Khartoum.

The main two tributaries to the Blue Nile are Dinder and Rahad

Rahad Station:

The station of River Rahad is located at El_Hawata. River Rahad is one of the main two tributaries to the Blue Nile. It joins the Blue Nile just downstream Medani.

Dinder Station:

The station of Dinder station is located at Gwasi. River Dinder is the second tributaries to the Blue Nile. It joins the Blue Nile upstream the junction with Rahad.

Jabal Awliya Dam Station:

There is an upstream reading, downstream reading and discharge measurement. It’s located in the White Nile River upstream Khartoum State.

Tamaniat Station:

Its located downstream Khartoum State, it’s an important station, because it gives the summation of the Blue Nile and White Nile during the low season.

2.3 Collected data

For the purpose of this research, a visit to Sudan has been made from 5th of November 2007 to 14th of December 2007. The data have been collected from different cities and ministries. Data were collected from:

- Rossieres (more than 500 km from Khartoum)
- Sinnar Dam (more than 350 km from Khartoum)
- Hydraulics Research Station (HRS) in Medani (around 180 km from Khartoum)
- Directorate of dams in MOIWR
- Directorate of Water Resources in MOIWR
- Remote Sensing Unit, Survey Department and Water Resources Department in Khartoum University.
- Ministry of Metrology
- Ministry of Civil Defence.
- Ministry of Agriculture
- Meirag Company and
- Dar Consult.

2.3.1 Discharge and water levels data:

The discharge and water level were collected for Eddiem, Rossieres, Sinnar, Medani, Khartoum, Jabal Awliya and Tamaniat. The data was collected for the years 1999 to 2007. The data are complete for the all stations, very few missing days in the data.

2.3.2 Rainfall data

The rainfall data was collected for the important cities like Rossieres, Sinnar, Medani and Khartoum. Data in stations between these cities were not collected because of the price of data. The data was collected also for the years 1999 to 2007.

2.3.3 Tributaries to the Blue Nile

The discharge and water level for the main two tributaries Rahad and Dinder to the Blue Nile were collected for the years 1999 to 2007. Rahad and Dinder are seasonal rivers. They contribute with an influential amount of water.

2.3.4 Cross sections of the Blue Nile

The cross sections of the Blue Nile from Rossieres to Sinnar and from Sinnar to Khartoum were made in 1991 for the development of FEWS. The intervals of the cross sections were not the same. Other detailed cross sections were made for the centre of Khartoum for the Blue Nile, White Nile and Main Nile in UNESCO_Chair_for_Water, (2002).

2.3.5 Abstraction Projects in the Blue Nile between Rosieres and Sinnar dam

The abstraction projects in the Blue Nile were calculated and collected in order to enhance the water balance in the Blue Nile. Moreover, the abstracted amount of these projects is substantial. It is important to check the water balance in the system for future building of 1D SOBEK model and to estimate the discharge at Khartoum.

The crop water requirement is calculated for these projects by determining first the total area for each project and each crop as shown in **Error! Reference source not found.** in the appendix, and then calculated the required water for each crop in a specific month as shown in Table 1 in the appendix. Finally multiply the total area for each crop and each project by the required water for each crop in a specific month as shown in the appendix in Table 2.

Gazira and Managil projects are the biggest agricultural projects in Africa under one administration. The area of this project is around 2.5 million Fadden, the abstraction by Gezira and Managil project is also determined in Table 3. The required water is calculated as an average of ten days in each month.

2.3.6 Damages of Flood

Information and data about damages of the flood were collected for recent years from 1998 to 2007, damages of the flood were collected for the Whole country, and especial consideration was made for Khartoum. More information and analysis is made in section 3.6 of this research. The collected data shows the death of people, casualties, death in animals, destroyed houses, destroyed trees. For the year 2007 the damage cost is calculated in Khartoum from the flood is more than 45 million US dollars.

2.3.7 Free web sites

Some free web sites were used for collecting some data such as:

- This site allows to download the ASCII file for the selected region http://www.ambiotek.com/srtm
- This following site shows how SRTM work.
  http://www2.jpl.nasa.gov/srtm/SRTM_paper.pdf
- The following site shows the Arc Hydro Tools. The Arc Hydro Tools set is a suite of tools which facilitate the creation, manipulation, and display of Arc Hydro features and objects within the ArcMap environment. The tools provide raster, vector, and time series functionality, and many of them populate the attributes of Arc Hydro features. The site contains the zip file of the Arc Hydro Tools setup file as well as several documents describing what the tools are and how to use them.
  http://www.crwr.utexas.edu/gis/archydrobook/ArcHydroTools/Tools.htm
- The following site shows how the Arc Hydro Tools working in the Java environment interface.
  http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html
- The following site contains the global flood archive as an animated image. You can visualize your concerned area.
  http://www.dartmouth.edu/~floods/Archives/GlobalFloods1985-2007.gif
- The following site shows an image of flood analysis with MODIS Terra & Aqua Imagery Recorded on 29 May and 2-4 September 2007. http://www.reliefweb.int/rw/fullMaps_Af.nsf/luFullMap/170F93434EDCD079852573530058FC51/$File/unosat_FL_sdn070910.pdf?OpenElement
- The following site contains some remote sensing images before the flood and during the peak of the flood.
  http://www-misr.jpl.nasa.gov/gallery/galhistory/2001_aug_29.html
- The image of contour map of Khartoum in a Pdf format http://www.unsudanig.org/rco/data/flood/map/Map%201105%20Khartoum_Potential_Flood_Zones_2007_v2.pdf

2.3.8 Reports

For the purpose of this research, many reports have been collected from different sources such as HRS library, General directorate of Dams, Rossieres Dam, Sinnar Dam, and Ministry of Civil Defence…etc. All these documents have been scanned and well documented in one folder. They will be free and available for anyone who wants to continue further more with this research or relevant work.

2.4 Preparation and validation of data

The first stage was the preparation of the water level, discharge and rainfall data. The data was prepared in excel format for better understanding and interpreting of the data. For this purpose the macro tool in Microsoft Excel have been used to prepare the data in annual basis. When you record a macro, Excel stores information about each step you take as you perform a series of commands. You then run the macro to repeat, or "play back," the commands. The data was put also in a time series format. Short period of flood season was also made for better visualization to the flood season.
The data have been subjected to a quick check for the odd data. There were some errors in the data due to human errors in the field or mistakes due to data entry. Sometimes, data is missing and in some cases numbers have been swapped (Figure 2.6).
The data have been checked by comparing the hydrographs of a certain station with the downstream station and upstream station. Moreover, the data for the same station have been checked with the previous year and the next year.
Many problems appeared at this stage, and sometimes data appeared to not even present what it was supposed to present. After careful checking and contacting the source to review the data, corrections have been made.
There are some missing data in the duration of study period (1999-2007), and sometimes the missing data extends for more than two weeks (Figure 2.5). It's recommended to fill those gaps by any good method.

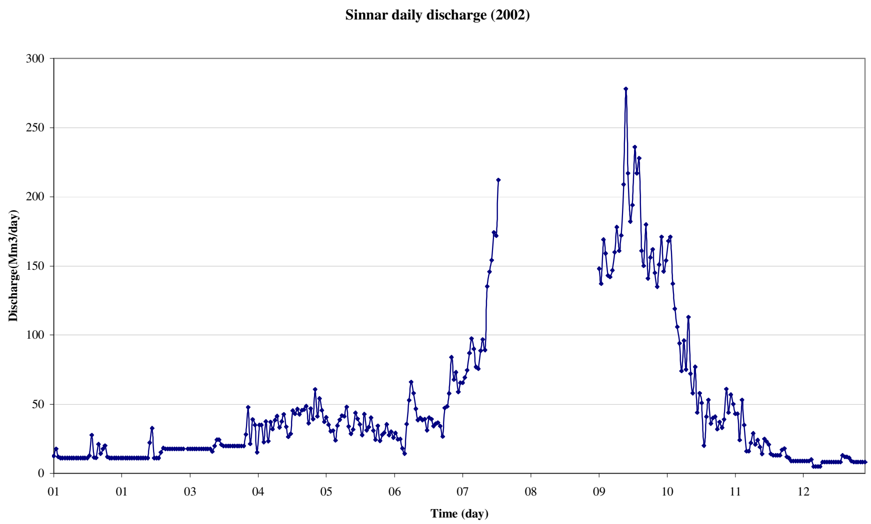

Figure 2.5 Missing discharge data from 20/7/2002 to 1/9/2002

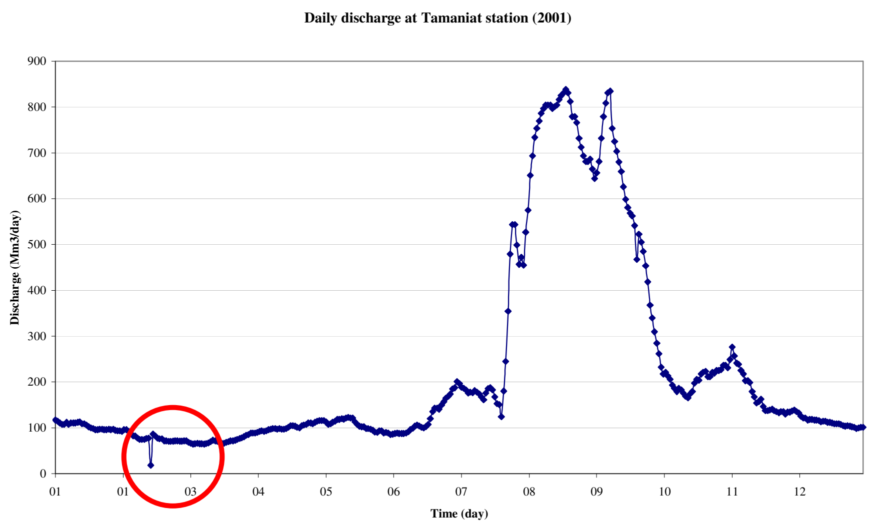

Figure 2.6 Swapped number in daily discharge at Tamaniat station (81 to 18)

3 Flood analysis

In this chapter the causes of the flood in Khartoum will be explained, the opinions of the experts will be discussed about the effect of local rainfall in Khartoum. After that a rainfall analysis for Eddiem, Damazine (Rossieres), Sinnar and Khartoum will be made. Then, a runoff between Rossieres and Sinnar will be calculated from the available two rainfall stations. After that a discharge analysis will be made. Finally, the damages of the flood will be calculated.

3.1 Causes of Flood

One of the causes of the floods in Khartoum is an increase of water level above the bank of the river channel, after prolonged precipitation over large areas of a basin which, can also exceed the conveyance capacity of river channel, hence leading to flooding. Normally, river flood last for several days to several weeks and usually affects large areas.
The threshold water level, which is determined by the FEWS model, is 16.5m; Figure 3.10 shows the threshold water level in Khartoum. The generation of flood in Khartoum occur due to high rainfall in the upper catchment in Ethiopia.

3.2 Effect of local rainfall

The effect of local rainfall will be discussed in the following section. Opinions of experts are highly recommended to be considered.

3.2.1 Opinions of specialists about the effect of the local rainfall

In the travelling to data collection in Sudan, relative reports and literature reviews have been made about the effect of the local rainfall in Khartoum. But unfortunately there were no reports about this important event. So information was gathered from the opinion of the experts on this field as explained below:

Dr. Jamal Mortada from Khartoum University thinks that from his point of view the damages of the flood in Khartoum are due to lack of proper drainage system. Moreover, the rainfall occurs 6 to 7 times during the flood season with the little amount of rain in Khartoum, and the effect of the rainfall is neglected.

Dr. Said Drman who works in the Ministry of Metrology, said the effect of the local rainfall is, when the people near the affected areas and the government are working to make temporary barriers (filling sand bags), and the rainfall comes, it slows or prevent the people to finish the work. Another problem he said, the rainfall water can't reach the River. He said the main cause for the flood in Khartoum is due to the rainfall in the upper catchment Ethiopia.

Dr. Abdalla Khiar, who works in the Ministry of Metrology, said there is a great effect of the local rainfall, he said just a 10km * 10 km areas will contribute so much to the runoff, He said the water which comes to Khartoum is not only the water that comes from the upper catchment Etiopia and the main two tributaries Rahad and Dinder, but from the rainfall also along the Blue Nile in Sudan. Another Example he gave, is a dam in the north of Khartoum at the Main Nile, they built a dam for water harvesting and the capacity of that dam is 5 $Mm^{3,}$ and after one rainfall the whole dam was filled.

Experts claim however that also local rainfall cases flooding in Khartoum. In 1988 a high water level accompanied by 210 mm rainfall in one day.

From the above discussion we conclude that:

- The opinions about the effect of local rainfall are contradicting.
- Lack of proper drainage system causes a lot of damages.
- The rainfall amount at Khartoum is low compared with upstream cities along the Blue Nile.
- Rain fall itself slows or prevent the work of people who building temporary barriers.
- Temporary barriers prevent the water to drain to the river.
- A water harvesting dam at the Main Nile in northern of Khartoum shows great amount storage (5Mm^3) after one rainfall.

3.3 Rainfall analysis

Rainfall has a great effect in social and economical life. Scarcity in rainfall leads to drought while an excessive rain in a short period of time leads to floods. In 1984, the year of the drought in Sudan, Khartoum received only 4.7 mm of rain between May and October. A famine hit Sudan as a consequence of crop failure, and people migrated to search for food and water. In 1990 there was also little rainfall (4mm).

Floods reflect the other extreme in rainfall fluctuations. It occurs when a rainfall during a short period of time, is well above average. We must look to many factors in order to determine the severity of the flood, such as the slope of the land, the soil type and the amount of water in the soil. In the 4th of August 1988, Khartoum was hit by 216 mm of rainfall during a period of 24 hours. This situation became disastrous when the Nile rose around 7m above normal, which led to wide spread damages in properties of people in Khartoum.

A rainfall analysis to the stations along the Blue Nile will be made below. Special consideration will made to the months which expect damages due to local rainfall. Moreover we will look how the rainfall varies from the upstream stations to the downstream stations. Any average monthly rainfall less than 20 mm/month will not be considered in the analysis of the water balance.

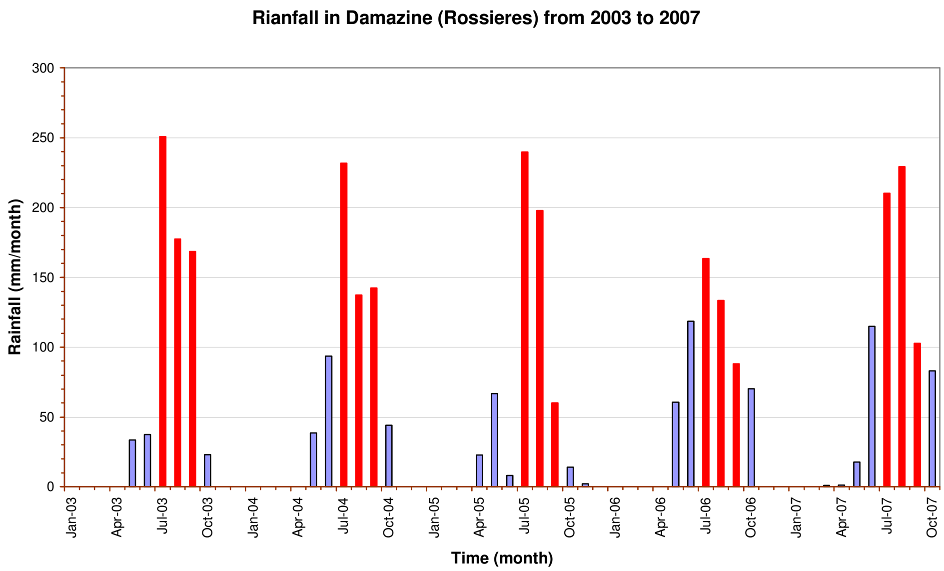

Figure 3.1: Rainfall in Damazine from (2003 to 2007).

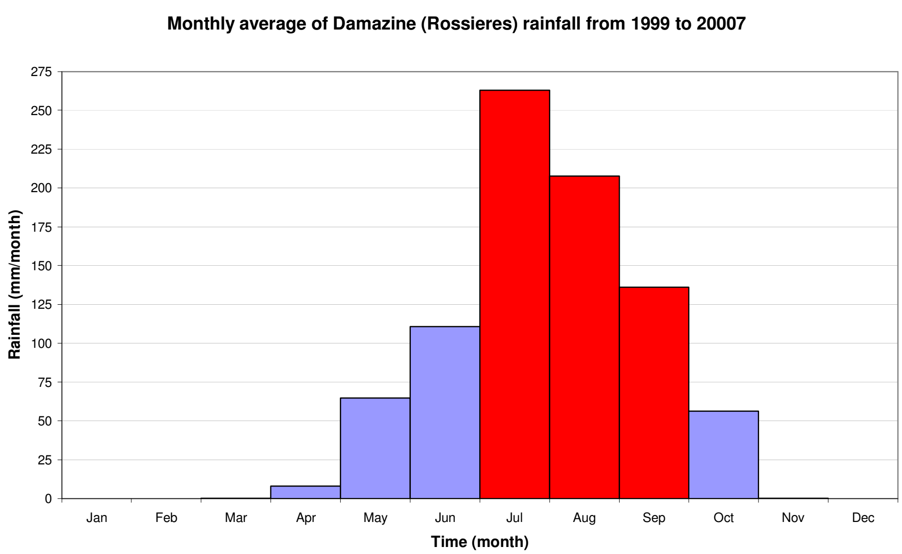

Figure 3.2: Monthly average of damazine (Rossieres) rainfall from 1999 to 2007.

Damazine station is located at 11.81 latitude line and 34.39 longitude line. In Damazine station which is beside Rossieres, the rainfall occurs normally from May and October, and the highest rainfall occurs from July to September. (Figure 3.1).
For the average monthly rainfall from 1999 to 2007 we found that from Figure 3.2, the rain decreases gradually from July (260 mm/month) to September (140 mm/month). In addition, we infer that the highest contribution to the flow in the Blue Nile occurs in July. Moreover, the sudden increase of rainfall from June to July may cause high damage to Rossieres city due to local rainfall. There is a rainfall station at the same sub catchment which called Bau. It's recommended to be used in future analysis.

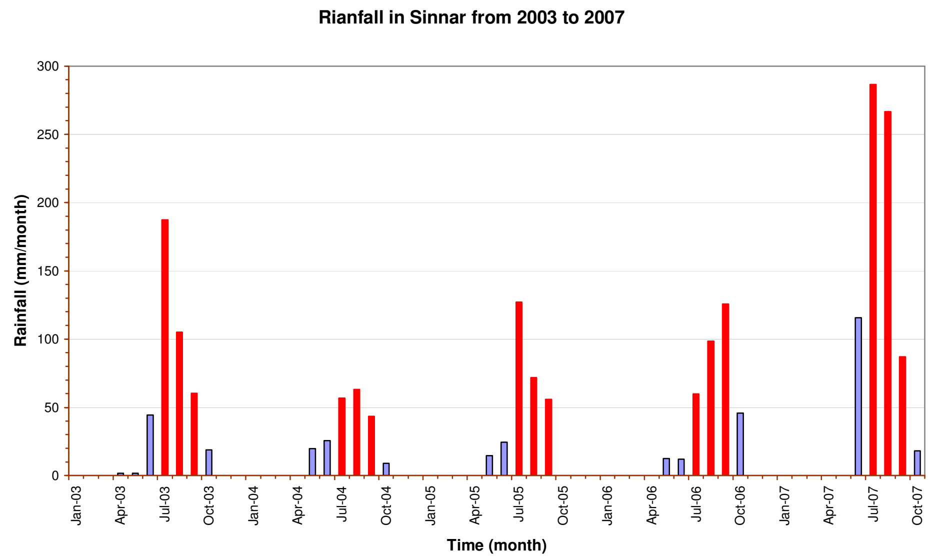

Figure 3.3: Rainfall in Sinnar from (2003 to 2007).

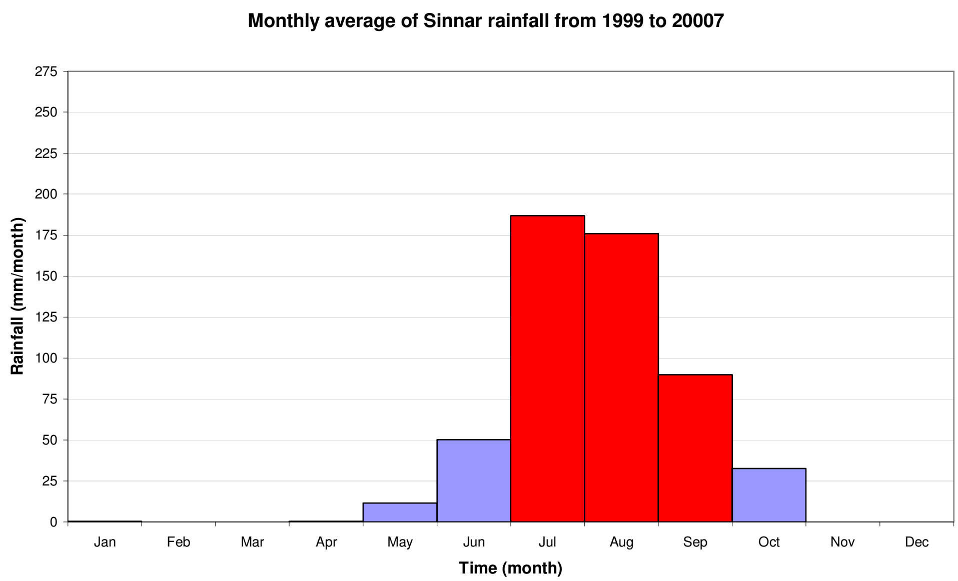

Figure 3.4: Monthly average of Sinnar rainfall from 1999 to 2007.

Sinnar station is located at 13.54 latitude line and 33.63 longitude line. In Sinnar station also the rainfall normally extends from June to October, and the highest rainfall extends from July to September. (Figure 3.3). The rainfall during July and August in 2007 was high compare to previous years. For the average monthly rainfall from 1999 to 2007 we found that from Figure 3.4 the rainfalls in July and August are near to each other and around 180 mm/month. In September there is a sudden drop in the amount of rain to around 90 mm/month. In addition, the contribution of Sinnar sub-catchment to the river flow will be a lot during July and August. The damage due to local rainfall in Sinnar city is expected to be in July and August. There is a rainfall station at the same sub catchment which called Umm Benen. It's recommended to be used in future analysis.

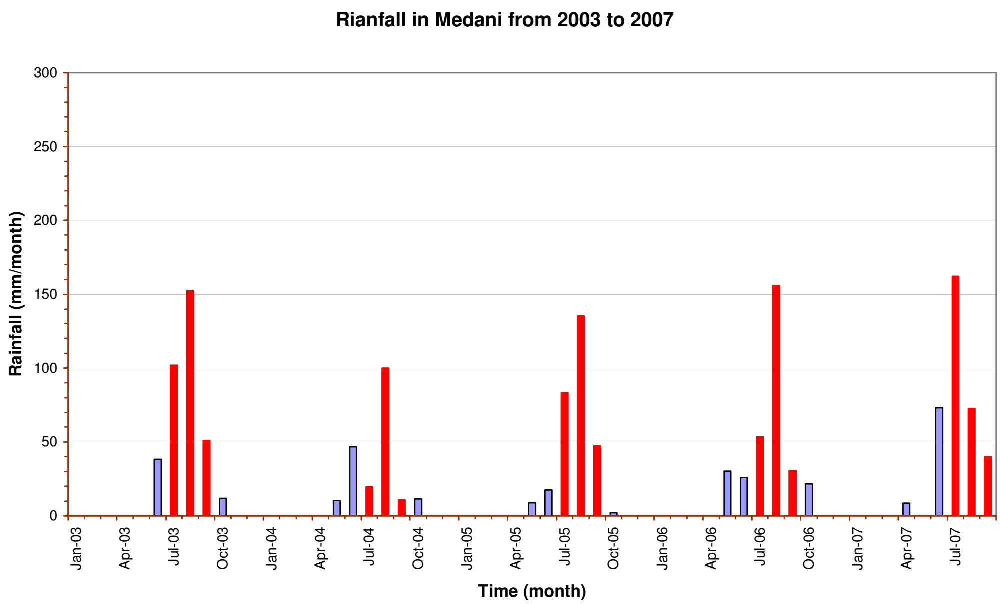

Figure 3.5: Rainfall in Medani from (2003 to 2007).

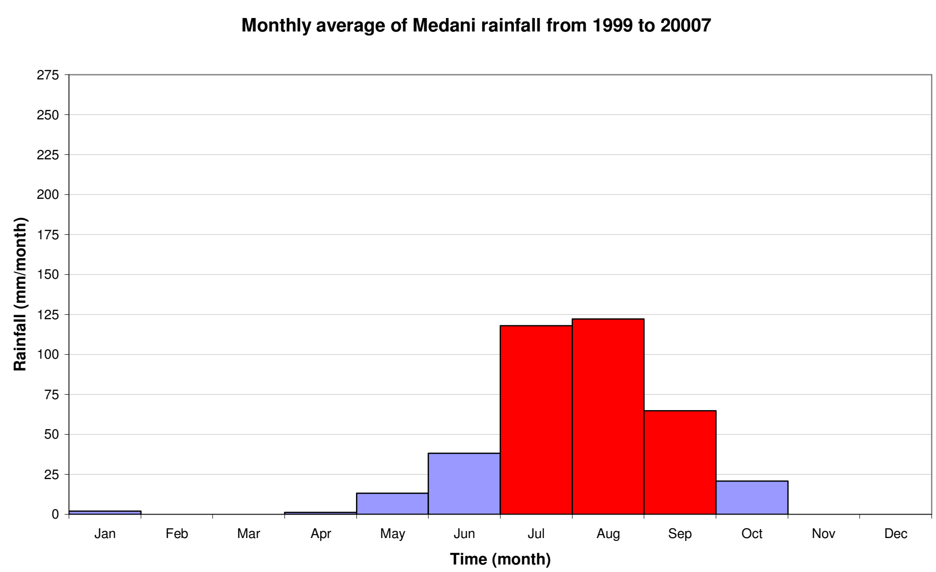

Figure 3.6: Monthly average of Medani rainfall from 1999 to 2007.

In Medani station the rainfall extent from June and September. There is little rainfall in October compare with other months at the same station and compare with upstream stations. The rainy season extend from July to September. (Figure 3.5). For the average monthly rainfall from 1999 to 2007 we found that from Figure 3.6 the rainfalls in July and August are almost the same and around 120 mm/month. But, unlike the upstream stations, the average monthly rainfall in August is a little higher than July. The contribution to the Blue Nile flow is high during July and August. The damage due to local rainfall in Medani is expected to be in July and August.

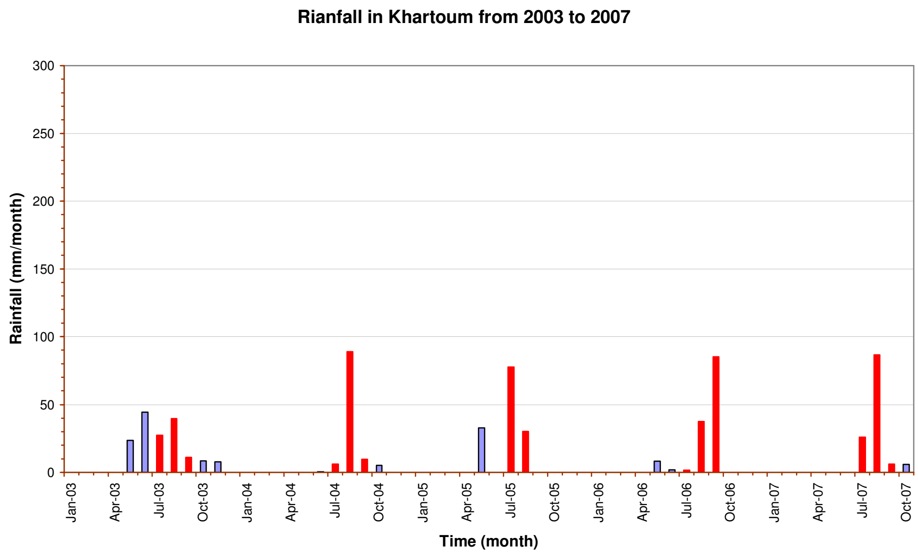

Figure 3.7: Rainfall in Khartoum from (2003 to 2007).

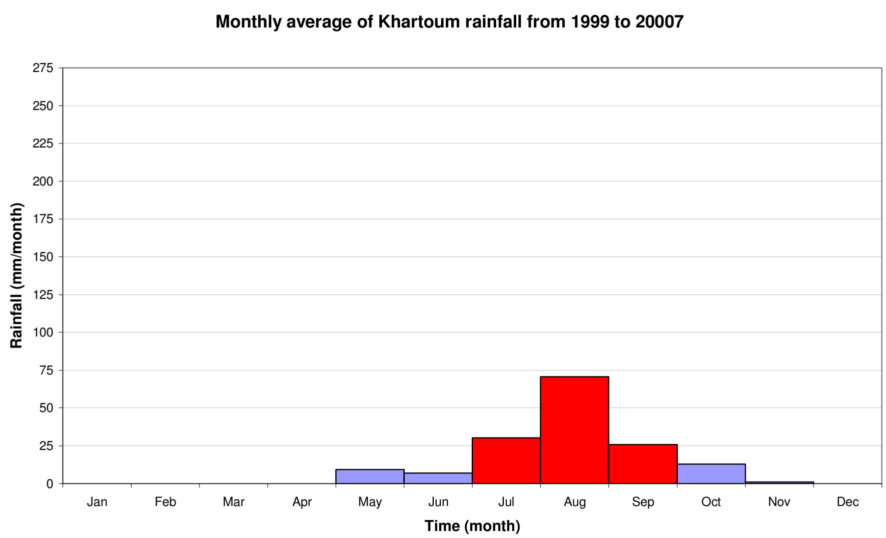

Figure 3.8: Monthly average of Khartoum rainfall from 1999 to 2007.

In general the rainfall in Khartoum is much less than the other three upstream stations. From Figure 3.7 we noticed that the rainfall occurs between July and September. In August 2007, 6 consecutive rainfall events occurred in 20 days. That means the average period between rainfall events is around three days, which means the soil was saturated an another rain event came, which will lead to more overland flow and more discharge to the river. From Figure 3.8 we found that the rain in August (72 mm/month) is much more than July and September (around 29 mm/moth). Khartoum is one of the highest populated cities in Sudan. Although the average monthly rainfall is not high like the upstream stations, but it could cause a lot of damages due to local rainfall. It's clear that the local rainfall may cause damages during August. The worst scenarios may occur at this month.

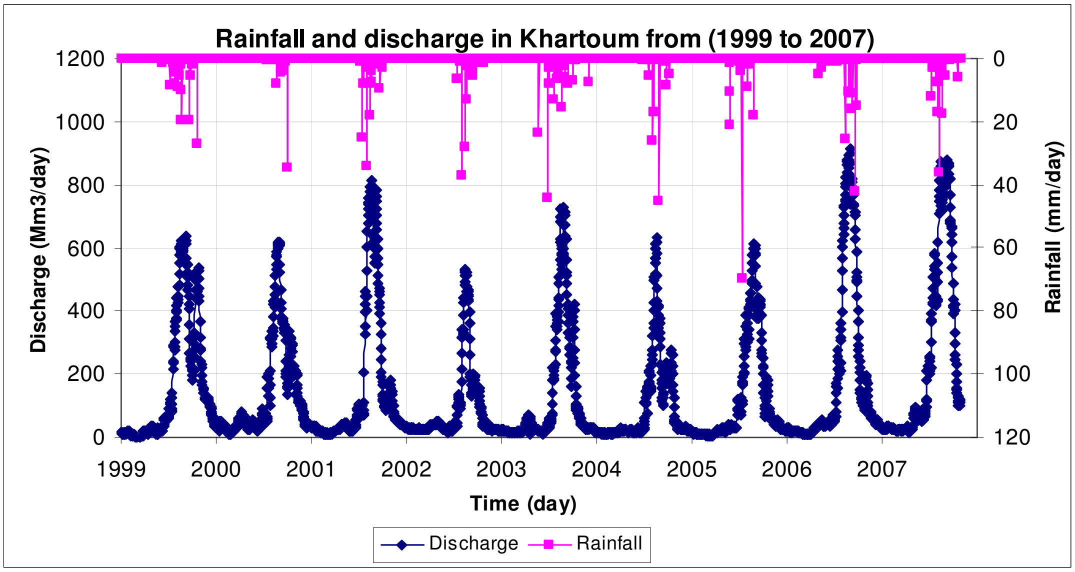

Figure 3.9: Rainfall and discharge in Khartoum from (1999 to 2007).

From Figure 3.9 we notice that there is a relation between the peak of flow and the highest rain during the flood season in many years, and the peak of the rainfall is a little earlier than the peak of the flood.

3.4 The threshold of the flood at Khartoum

It is very important to know the threshold of the flood in Khartoum.

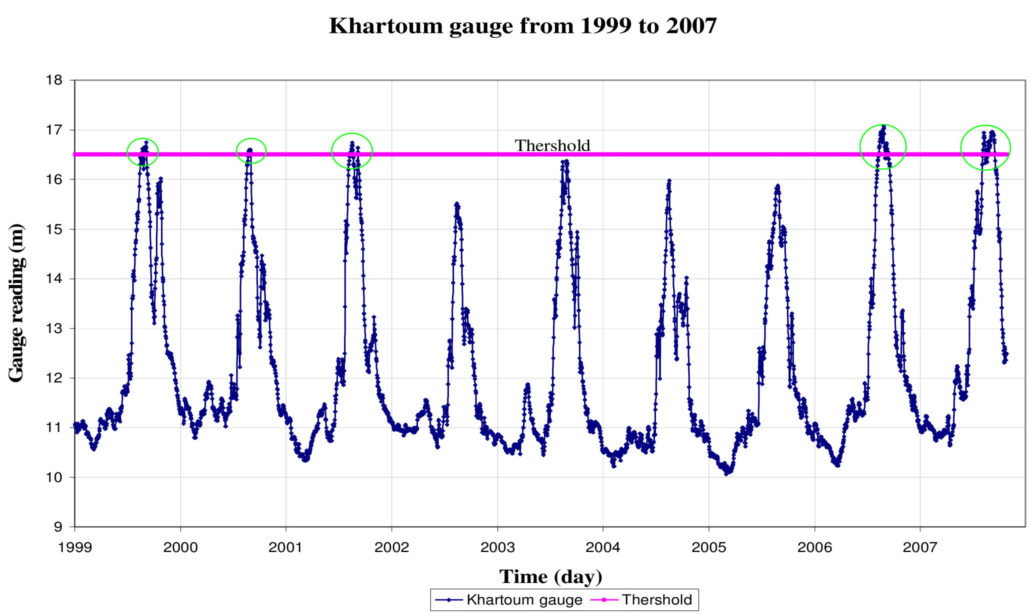

Figure 3.10: Khartoum time series of gauge reading with the threshold of the flood.

Figure 3.10 shows the threshold of the flood which is determined in FEWS model in Sudan. It is obvious that there is river flood in 1999, 2000, 2001, 2006 and 2007. From the trend of the time series in Figure 3.10 for the years 2006 and 2007 the flood was high compared with the previous floods.

In Current FEWS which is used in Sudan, the limit for warning by the water level at Khartoum is as shown in Table 3.1.

Table 3.1: Warning for flood in Khartoum by existing FEWS

Warning	**Alert (m)**	**Critical (m)**	**Flooding (m)**
Water level	15	16	16.5

3.5 Rainfall runoff between Sinnar and Rossieres

The catchment between Sinnar and Rossieres in the Blue Nile contribute with a considerable amount of flow to the Blue Nile. During the flood season (July to September) the average monthly rainfall at July decreases from 260 mm/ month in Rossieres to 185 mm/month in Sinnar, at August from 210 mm/ month in Rossieres to 175 mm/month in Sinnar, and at September from 136 mm/ month in Rossieres to 90 mm/ month in Sinnar.
The relation between the rainfall and runoff is complicated and subjected to many factors. Some assumptions will be taken in this calculation. The catchment was represented only by two stations because of the cost of data. The catchment was divided to three sub-catchments. The northern catchment represented by Sinnar station and the southern catchment represented by Rossieres station. The middle catchment divided between the two stations. Each catchment got its own runoff coefficient as shown in the literature review in section 1.4.7. The rainfall consider to be effective when it's more than 20 mm/day Abbas et al, (1999).
The flow from the catchment has been calculated by using the rational method.

The Rational equation is the simplest method to determine peak discharge from drainage basin runoff. It is not a sophisticated method (Chow et al., 1988).
Rational Equation:

$$Q = CIA$$

The Rational equation requires the following units:
Q = Peak discharge, m3/day.
C = Rational method runoff coefficient.
I = Rainfall intensity, m/day.
A = Drainage area, m2.

The assumption for the areal average rainfall within the sub-catchments depends on the location of the rainfall stations. Table 3.2 explains these assumptions.

Table 3.2: Aereal coverage assumption for the rainfall distribution.

Sub-catchment	Rainfall distribution
North	Sinnar
Middle	Sinnar/2 + Damazine/2
South	Damazine

The calculated flow will be used in water balance in chapter 4.

3.5.1 Discharge analysis

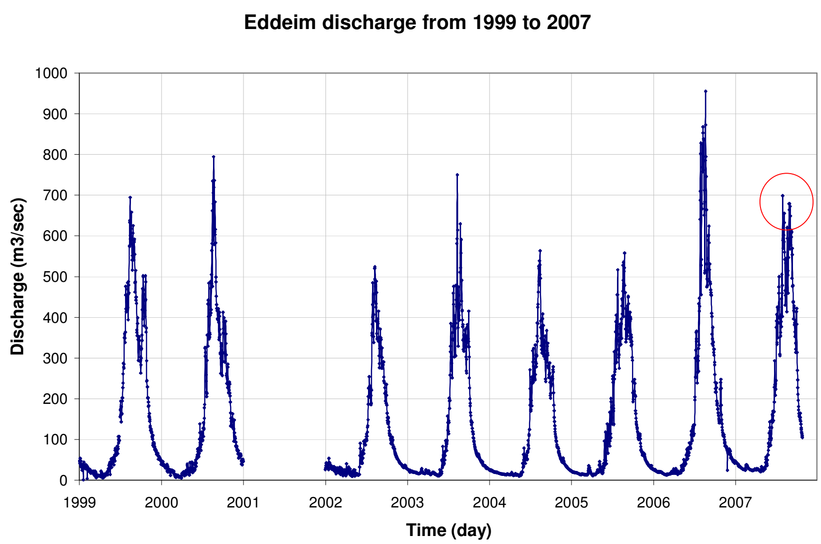

Figure 3.11: Eddeim discharge from 1999 to 2007

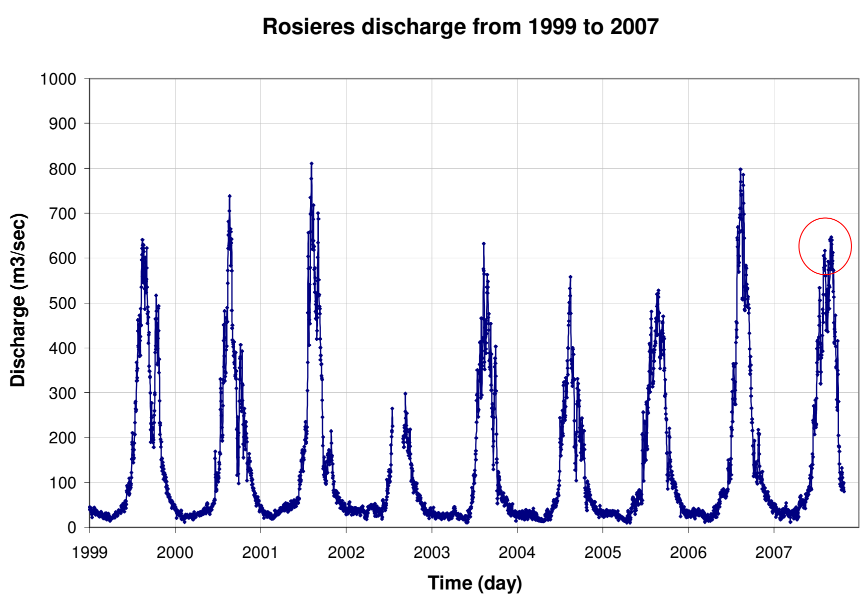

Figure 3.12: Rosieres discharge from 1999 to 2007

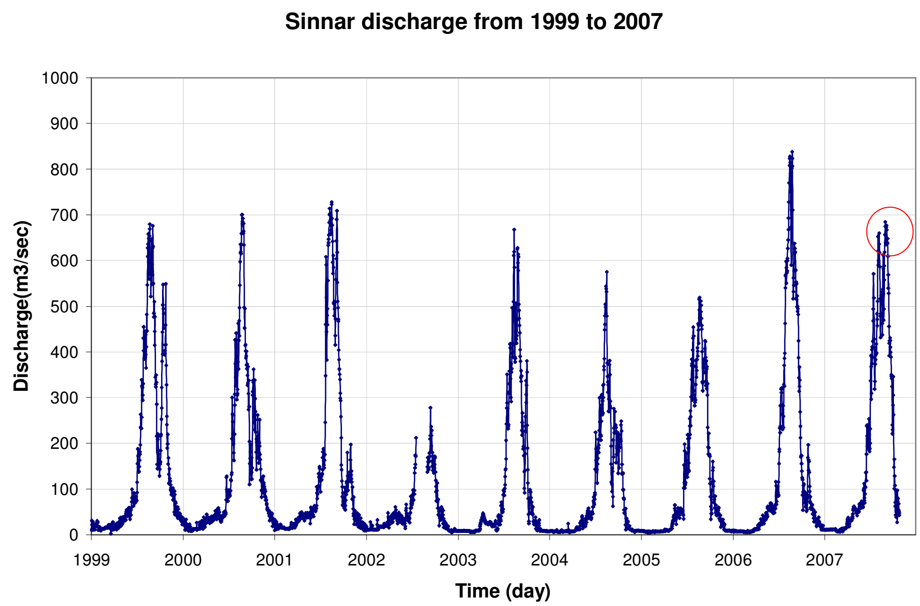

Figure 3.13: Sinnar discharge from 1999 to 2007

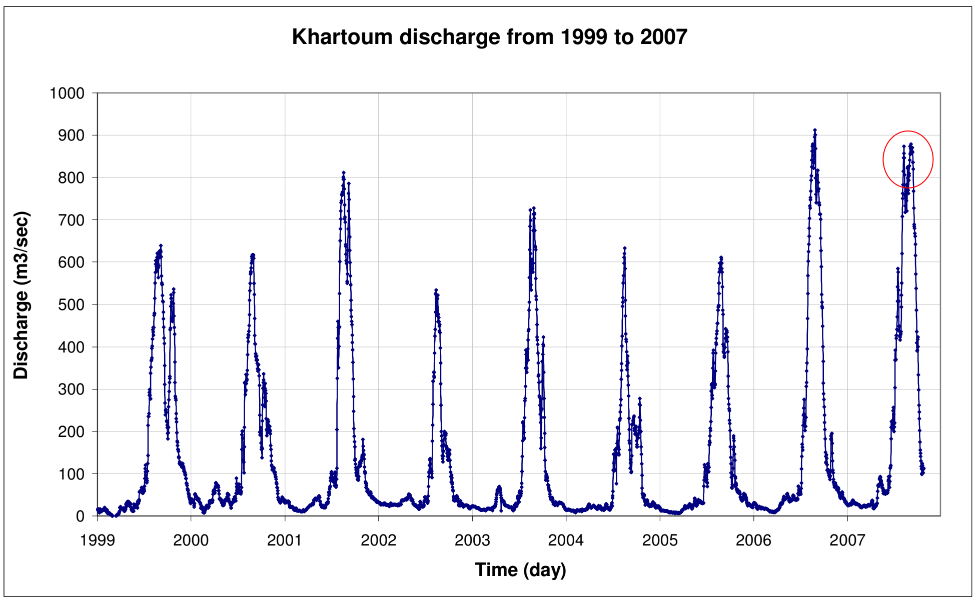

Figure 3.14: Khartoum discharge from 1999 to 2007

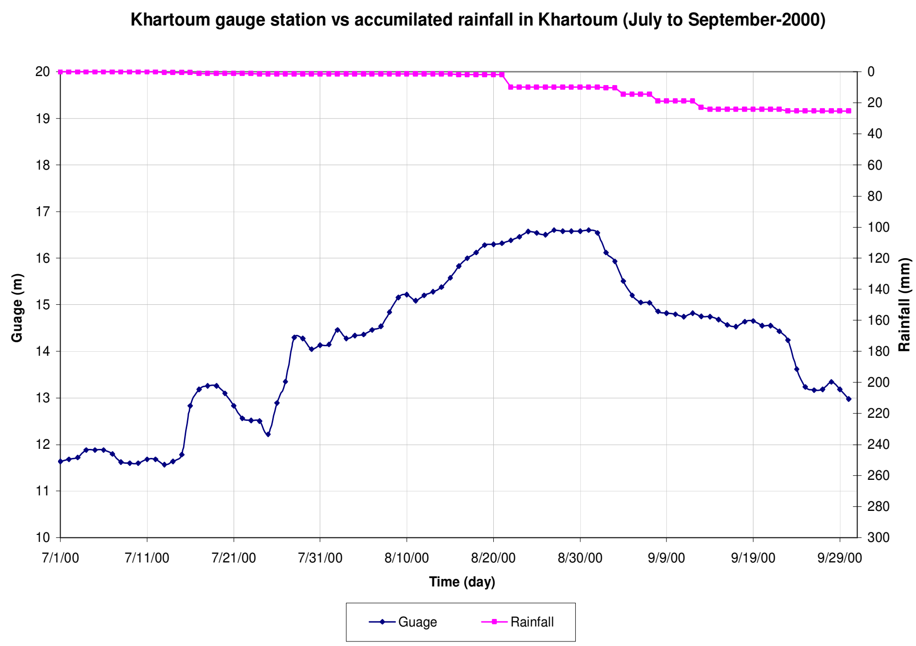

Figure 3.15: Accumulated rainfalls and water levels at Khartoum from July to September 2000.

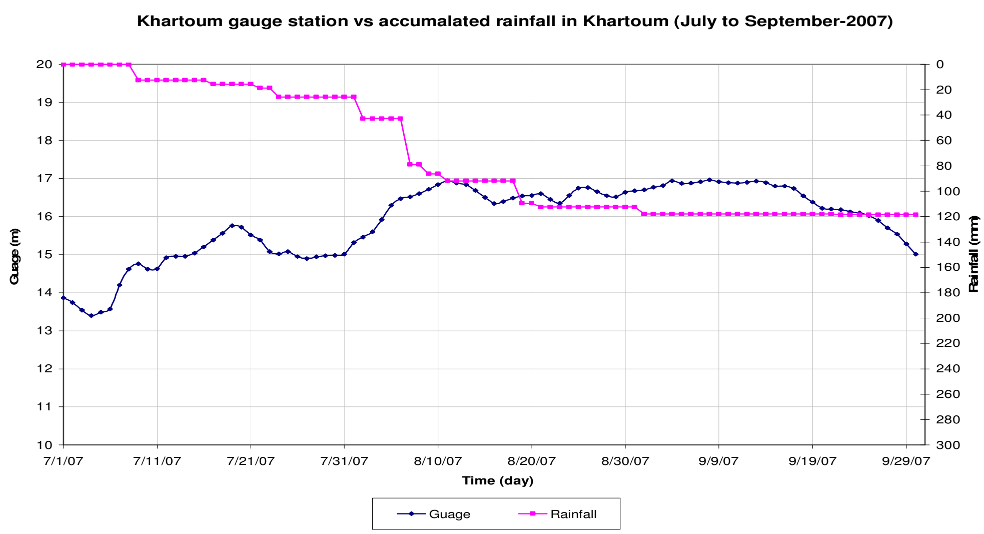

Figure 3.16: Accumulated rainfalls and water levels at Khartoum from July to September 2007.

From Figure 3.11 , the discharge time series for Eddiem station from 1999 to 2007 shows that for the year 2007 we can notice that the discharge is low compared to 1999, 2000, 2001 and 2006. Similarly, in Figure 3.12, the discharge time series for Rossieres station is also low for the year 2007 compared with the other flood years at the same station. If we move downstream to Sinnar station as shown in Figure 3.13, we found that also in the discharge time series for the year 2007 is also low compared with the other flooded years. However, for Khartoum time series, the discharge for the year 2007 is high as shown in Figure 3.14, and almost the same as in 2006 and even higher than in 1999, 2000 and 2001. We can infer from that, there is an effect of local rainfall which causes the discharge to increase rapidly at Khartoum station.

In addition, if we look at Figure 3.10, we found that in both 2000 and 2007 there was a flood. However, from Figure 3.15 for the accumulated rainfalls and water levels at Khartoum from July to September 2000, we found that the flood is from the river only because the rainfall was very little. On the other hand from Figure 3.16 for the accumulated rainfalls and water levels at Khartoum from July to September 2007, the flood is from the river and accompanied by the local rainfall. It can be seen that in 2000 the flood is not accompanied by local rainfall, whereas in 2007 it accompanied by about 120 mm. this explain why the damages are high in 2007. The coming section will show in details about the damages of the flood in Sudan, and in more details the damages of the flood in 2007.

3.6 Damages of flood

From the Ministry of Civil Defence, which consists from soldiers, who responsible for natural disasters in Sudan. There are some statistics that show the damages of the flood in Sudan for different years. From Table 3.3 to Table 3.10 we found that the damage of the flood affects different sectors and different levels. However, the condition of the flood for 2002 is alert from Table 3.1. For the year 2003 the river is almost flooding. The following tables will show the damages of the flood in Sudan.

Table 3.3 Damage of building due to flood.

Years	Affected states	Affected provinces	Affected villages and cities	Affected families	Affected individuals
1999	17	40	562	292429	1452152
2000	9	22	57	7850	89974
2001	16	35	340	21217	120025
2002	13	20	163	2817	304961
2003	12	25	1148	34194	125175
Total	67	142	2270	358507	2092287

Table 3.3 above shows the effect of the flood from a big scale to small scale. It shows the effect for the years from 1999 to 2003. Recent years are not included on this table. The minimum damage occurred in the year 2000 because it's a river flood only, and it was not accompanied by local rainfall. The highest damage occurs in the year 1999.

Table 3.4 Injuries and died people directly from flood in Sudan (1998-2006)

Years	Injuries	Death	Total
1999	76	125	201
2000	13	53	66
2001	0	4	4
2002	9	37	46
2003	217	35	252
2006	20	38	58
Total	363	347	710

Table 3.4 shows the injured and died people in Sudan from flood from 1999 to 2006. The effected people in 2004 and 2005 either small or no one effected. The highest death also occurs in 1999.

Table 3.5 Number of casualties and number of people with health problems as a consequence of floods

Years	Sick	Death	Total
1999	70560	299	70859
2000	99353	320	99673
2001	1412	2	1414
2002	201	28	229
2003	217	35	252
Total	199544	704	200248

Flood may bring many diseases and water-borne diseases. Contaminated drinking water by floodwater may carry a lot of micro-organisms which can produce diarrhea, hepatitis, typhoid, tetanus…etc. The flood can be even more dangerous when it nock people down or causes people to drawn, especially children. Table3.4 shows the death and illness due to flood from 1998 to 2003.

Table 3.6: Number of public places and services affected by floods

Years	Social	Water and Electricity	Education	Health	Others
1999	272	76	438	304	195
2000	5034	21	66	91	182
2001	13	34	6	7	132
2002	3	0	86	17	1642
2003		317	728	123	1427
Total	5514	498	2149	636	3959

The public places and services also affected by flood as shown in Table 3.6. We see that the flood affected the public places which serve the whole community, and this damage reflects in the entire society.

Table 3.7: Houses completely effected and partially effected by flood

Years	Partially	Completely	Total
1999	43753	73291	177044
2000	6985	873	7848
2001	8978	9390	18368
2002	5950	2950	8900
2003	27180	12705	39885
Total	116730	119209	235939

As a result of flood, some houses are completely destroyed while other houses are partially destroyed. Table 3.7 shows the affected buildings by flood. The government has limited source, the effected people suffer a lot when they loose their own shelter.

Table 3.8: Agricultural losses due to flood (number of destroyed plants and trees)

Years	Palm and small trees	Fruits
1999	0	6300
2000	0	305
2001	40000	12500
2002	11223	0
2003	17000	646
Total	1304331217	142351

The agricultural sector in Sudan was affected by the flood. Table 3.8 shows the number of trees that died because of the flood. In some years we see that the damage is zero.

Table 3.9: Animals died due to flood

Years	Sheep	chickens
1999	8547	5220
2000	8750	12545
2001	250	0
2002	4527	0
2003	3845	11416640
Total	36815	11567076

Table 3.9 shows the dead sheep and chickens due to flood.

From Table 3.3) to table to Table 3.10) we learned that the flood causes a lot of damages almost every year, with different level of damages. It's important to know that the damage from Table 3.3) to Table 3.9) in the whole country and it's not only in Khartoum state. The flood of 1999 causes a lot of damages because it's also a river flood accompanied by local rainfall in Khartoum. However, the case in other cities could be different. It is clear that from the above tables that the flood affect all sectors of society and hit many areas in Sudan. Moreover, we can infer that, flood is a serious and frequent problem which repeated almost every two years.
From the report of 2007 Table 3.10), we noticed from the below table that 19 people died in Khartoum, and the cost of damage is high, the losses cost in Khartoum only more than forty five million US dollars (Table 3.9). So if we manage to install a good warning system and clean the drainage system we could save a lot of money. From Table 3.10) we can see that there are other states which suffered and destroyed even more than Khartoum. The highest damage cost was recorded in 2007 was in White Nile state, the damage cost was more than ninety eight million US dollars, and the collapsed houses were high. South Kordufan state also need more attention, the damage cost was more sixty two million US dollars. The collapsed number of houses was also high. The damage cost in North Kurdufan was not high, but the death at this year was high, 36 people died. We can see also that the damage at Khartoum is relatively high compare with other state, given that it is small state compared to other state. The main reason for the high cost of damage, because it is highly populated. The damage in the agricultural sector at Khartoum is very low because there are little activities of agriculture. The highest number of affected individuals was recorded in White Nile state, 168155 people. Then, South Kurdufan, 157625 people were affected. After that, 95915 people were affected in North Kurdufan. The fourth affected individuals were in Khartoum 76780.

Table 3.10 Damages in 2007

No	State	Collapsed houses		Casualties		Trees and animals		Roads and bridges		General public places	families	Individuals	Cost in pounds	Cost in dollars
		whole	partially	death	injuries	Trees	Animals	Roads	bridges					
1	Kasala	1766	3295	**15**	0	1243	2430	1	1	4	5061	25305	46370450	23185225
2	West Darfur	570	2846	4	0	187	250	1	-	24	3416	17080	3250000	1625000
3	Red Sea	149	666	2	57	-	358	0	1	-	815	4075	855010	427505
4	South Darfur	388	1014	7	2	199	138	0	0	24	1402	7010	210829	105414
5	Algazera	4461	3017	8	13	193000	1261	0	0	706	7478	37390	51076390	25538195
6	Unity	5847	-	0	0	220000	-	0	0	-	5847	29235	31147000	15573500
7	Upper Nile	2785	4645	0	0	-	-	0	0	-	7430	37150	7430000	3715000
8	South Kurdofan	**17816**	**14009**	**19**	15	341568	3098		2	122	31825	**157625**	124223496	62111748
9	North Kurdufan	8352	10831	**36**	75	110730	13336	2	-	333	19183	**95915**	14920570	7460285
10	Khartoum	6807	8499	**19**	19	4	0			36	15356	**76780**	90356000	**45178000**
11	Alshamaliya	404	2127	4	4	53	0	1	1	40	2531	12655	7874345	3937172
12	Blue Nile	2018	3489	4	6	116000	928	0	0	117	5507	27535	20015000	10007500
13	Nile River	987	1076	2	2	2089	1400	1	0	69	2063	10315	19158010	9579005
14	White Nile	14917	**18714**	**21**	70	6500	949	2		88	33631	**168155**	197010900	**98505450**
15	Gadarif	3318	924	7	32	20000	0	2	1	3	4242	21210	13765000	6882500
16	Sinar	5831	4594	8	6	0	157	1	1	97	4161	20805	12161000	6080500
17	North Darfur	181	526	1	1	0	0			85	707	3535	707000	353500
18	Gongoli	0	2031	0	0	0	0	0	0	0	2031	10155	1015500	507750
19	Lakes	0	242	0	0	0	0	0	0	0	242	1210	121000	60500
20	Warab	0	250	0	0	0	0	0	0	0	250	1250	125000	62500
Total		76597	82795	157	302	1011573	24305	11	7	1748	153178	764390	641792500	320896250

4 Water Balance

4.1 Introduction

In this research a water balance between Eddiem and Rossieres, Rossieres and Sinnar, and Sinnar and Khartoum. The main reason for this water balance, if it shows good result, probably it will be sufficient to build a 1D hydro-dynamic model in the future, upgrade of the flood early warning system, and for preparing models for the Nile DSS development. It may be possible also to predict the discharge at Khartoum from the discharge at Eddiem. If the water balance shows a good result that means during the flood season we can use the discharge at Eddiem, operation rule of the dams, abstraction projects, discharge of main tributaries, and estimation of the rainfall to predict the discharge at Khartoum.

4.2 Water balance between Eddeim and Rossieres

The reach between Eddeim and Rossieres doesn't need a water balance. Because, the discharge at both stations is almost the same. There is a little flow contribution from small streams in the rainy season. Moreover, there is evaporation from Rossieres Lake. Finally the change in storage at Rossieres dam due to operation rule should be considered.

4.3 Water balance between Rossieres and Sinnar

$Q_{comp\_R} - Abs_{GM} - Abs_{project} - Evap = Q_{Bal\_S}$

Q_{comp_R}: Roseires Dam release
Abs_{GM}: Abstraction for Gezeraa and Managil Scheme.
$Abs_{project}$; Abstraction by Wad Hashim, El Safa, El Nayra, Kassab, El Busata, Wad Reif, Karkoj, El Suki, NW Sennar and others projects.
Q_{comp_S}: Sinnar Dam release.
Evap: Evaporation losses from Sinnar reservoir
Q_{Bal_S}: Sinnar Dam release computed by the water balance.

The percentages of the above variables during the peak of the flood are around:
$Q_{comp\_R} = 100\%$, $_{AbsGM} = 3\%$, $Abs_{projec} = 1.5\%$, Evap. = 0.3 and $Q_{Bal\_S} = 95\%$

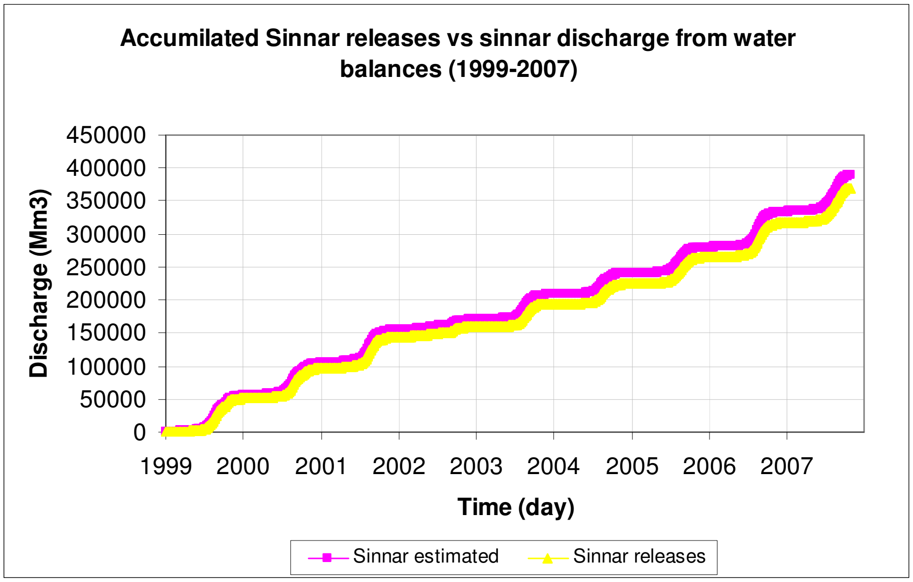

Figure 4.1: Sinnar estimated against Khartoum discharge from water balances (1999-2007).

Appendix C: Water balance

Table 4) in the appendix shows the water balance between Sinnar and Rossieres dam from 1999 to 2007.
For this water balance the abstraction for Gezera and Mangil Scheme was calculated for the summation of 10 days, so for daily water balance it is divided by 10 in order to get it per day.
For the abstraction projects between Sinnar and Roseris Dam it was calculated in monthly basis, so it was divided per month.
The rainfall runoff was calculated as shown in section 3.5 . For better water balance the lag time between Roseires and Sinnar should be considered, and it varied in flood season and low season. Moreover, the last survey for Sinnar Lake was in 1984. The designed capacity of Sinnar was more than 900 Mm3, but now it losses more than two third of its capacity by the sediment, and there is no rating curve which can show the content with the gauge.

Water balance for the reach between Rosseries and Sinnar Dam gave good results, but there is a little over estimation on the estimated discharge from the water balance. This is expected to come from the rainfall and the change in storage at the filling period of the dam. From the results of the water balance between Rossieres and Sinnar dam it can be concluded that the data is of good quality and is probably sufficient to build a 1D hydro-dynamic model. In addition, it may be possible to estimate the discharge at Sinnar by a water balance between Khartoum and Sinnar.

4.4 Water balance between Sinnar and Khartoum

$$Q_{comp\_S} + Q_R + Q_D = Q_{Khrt}$$

Q_{comp_S}: Sinnar Dam release.
Q_R: contribution of Rahad tributary .
Q_D: contribution of Dinder tributary.
Q_{Khrt}: Discharge at Khartoum.
The percentages of the above variables during the peak of the flood are around:
Q_{Khr}= 100%, Q_{comp_S}= 92%, Q_R= 2% and Q_D=6%.

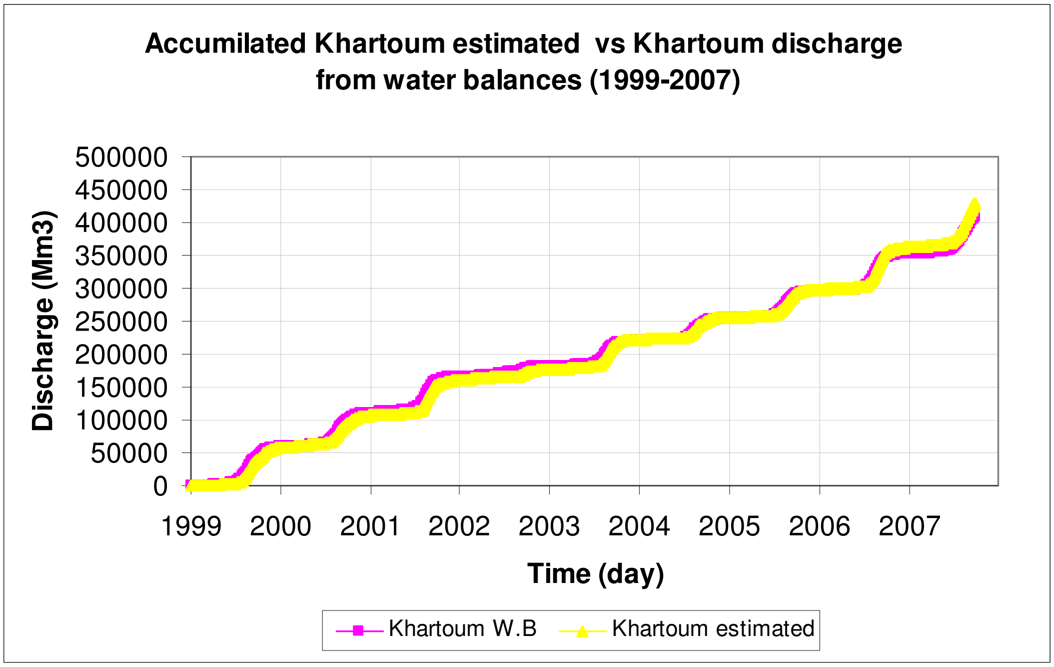

Figure 4.2 Khartoum estimated against Khartoum discharge from water balances (1999-2007)

Water balance for the reach Sinnar and Khartoum showed better results. The small differences of the two graphs are expected to be the effect of rainfall and abstraction projects. From the results of the water balance between Sinnar and Khartoum dam it can be concluded that the data is of good quality and is probably sufficient to build a 1D hydro-dynamic model in the future , upgrade of the flood early warning system, and for preparing models for the Nile DSS development. In addition, it may be possible to estimate the discharge at Khartoum by a water balance between Sinnar and Khartoum, it can give indication to the flood with a cross check with model predictions.

4.5 Problems for future development of 1D model

For future 1D model development for the Blue Nile, the following points should be considered:

- The distance between Eddiem station and Khartoum station is long (around 600 km), and the running time may take a long time.

- It needs a lot of cross sections to describe the long reach. There are only cross sections describing the reach between Eddiem and Rossieres Dam at the reservoir lake. In addition, the cross sections between Rossieres and Khartoum were made in 1991 and no any update for them since that time. Moreover, the intervals between the cross sections are not equal, and for some cross sections the interval is more than 5 kilometres.
- The content of Sinnar Dam is not known up to now, and there is no relation between the water level and the content of the reservoir lake is not known.
- The operation of Rossieres Dam and Sinnar Dam changes frequently due to the discharge from Eddiem, which need a special code for it.

5 Building the 2D model

5.1 GIS analysis

A GIS can be defined as a collection of computer hardware, software, and geographic data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. (http://www.gis.com/whatisgis/index.html).

Arc-GIS 9.2 is used in this research to georeference the free SRTM map and clipping for the desired area. More over it has been used to create shape files for the Nile River, crating counter maps to Khartoum, lowering the DEM of the river and converting the maps from one feature to another features.

5.1.1 Downloading SRTM map

The CGIAR-CSI GeoPortal is able to provide SRTM 90m Digital Elevation Data for the entire world. The SRTM digital elevation data, produced by NASA originally, is a major breakthrough in digital mapping of the world, and provides a major advance in the accessibility of high quality elevation data for large portions of the tropics and other areas of the developing world. The SRTM digital elevation data provided on this site has been processed to fill data voids and to facilitate its ease of use by a wide group of potential users. This data is provided in an effort to promote the use of geospatial science and applications for sustainable development and resource conservation in the developing world. Digital elevation models (DEM) for the entire globe, covering all of the countries of the world, are available for download on this site. The SRTM 90m DEM's have a resolution of 90m at the equator, and are provided in mosaiced 5 deg x 5 deg tiles for easy download and use. All are produced from a seamless dataset to allow easy mosaicing. These are available in both ArcInfo ASCII and GeoTiff format to facilitate their ease of use in a variety of image processing and GIS applications. Data can be downloaded using a browser or accessed directly from the ftp site. (http://srtm.csi.cgiar.org/).

The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. This data is currently distributed free of charge by USGS and is available for download from the National Map Seamless Data Distribution System, or the USGS ftp site. The SRTM data is available as 3 arc second (approx. 90m resolution) DEMs. A 1 arc second data product was also produced, but is not available for all countries. The vertical error of the DEM's is reported to be less than 16m. The data currently being distributed by NASA/USGS (finished product) contains "no-data" holes where water or heavy shadow prevented the quantification of elevation. These are generally small holes, which nevertheless render the data less useful, especially in fields of hydrological modelling. (http://srtm.csi.cgiar.org/).

The SRTM radars were unable to sense the surface beneath vegetation canopies and so produced elevation measurements from near the top of the canopies. Man-made objects, such as large buildings, roads, towers, and bridges are often problematic targets for radar imaging. Reflections, shadows, and smooth surfaces in built-up areas can often lead to severe layover, shadowing, and multi path artifacts. Given the 30-90 m posting of the SRTM data, only the largest man-made features are resolved, but the height of any urban SRTM pixel will be affected by the buildings within that pixel. Thus, heights measured in cities will represent average building sizes, rather than the height of the ground on which the buildings sit. Farr and Kobrick, (2005)

Steps to download the SRTM map: Alfonso, (2007)

- Download Google earth.
- Open the following link with Google Earth environment http://www.ambiotek.com/srtm
- Fly to Khartoum and click on "data for strm_43_09" as shown in figure5:1
- The actual data can be accessed from servers at Kings College London, UK or at the CGIAR CGNET in California. The nearest one should be selected, for this case UK server should be selected.
- Click on any FTP site as shown in figure5.1 to download a zipped ASCII file (be aware that the size of the zipped file could be up to 60MB).

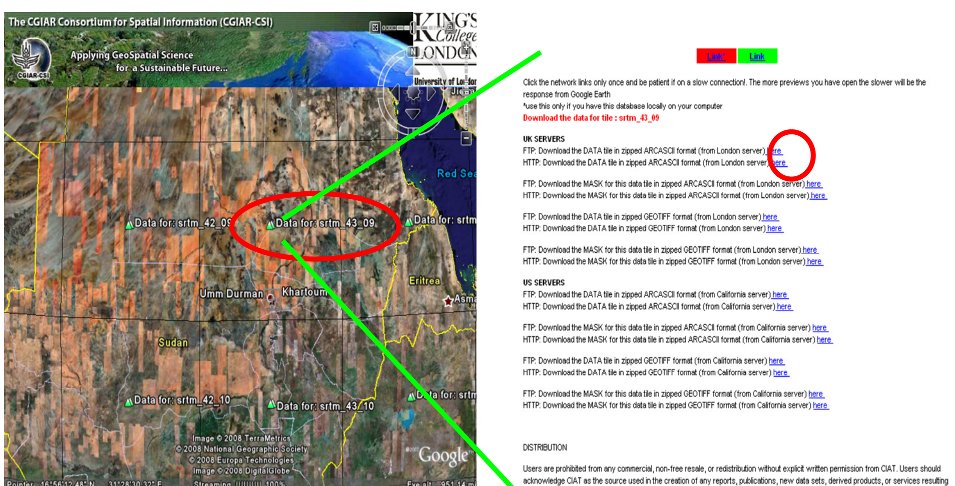

Figure 5.1 Download SRTM map of Khartoum

5.1.2 Preparation of SRTM map in GIS environment

Steps of preparing a DTM maps for the SOBEK by using GIS tool:

- First we open a folder of STRM; inside this folder is the required map.
- In this step we want to change our map from ASCII to Raster in order to clip our map as follow: Open ARC MAP > Conversion Tools > To Raster > ASCII to Raster > SRTM.
- Put the curser in the map to determine the corner of the map
- Data management Tools – Raster > Clip.
- Then we made a geo-referenced to our map as follows:

- ➢ Data Management Tools > Projection and Transformations > Define Projection > Clip Raster > Select > Geographic coordinate System > World > WGS 1984.prj > Apply > Ok.
- ➢ Data Management Tools- Projection and Transformation > Raster > Project Raster > Clip > Select > Projected Coordinate Systems > UTM _ WGS1984 _ 32N > Apply > Ok.
- The next step is to allow SOBEK to read the ASCII file: first Conversion Tools> Raster to ASCII

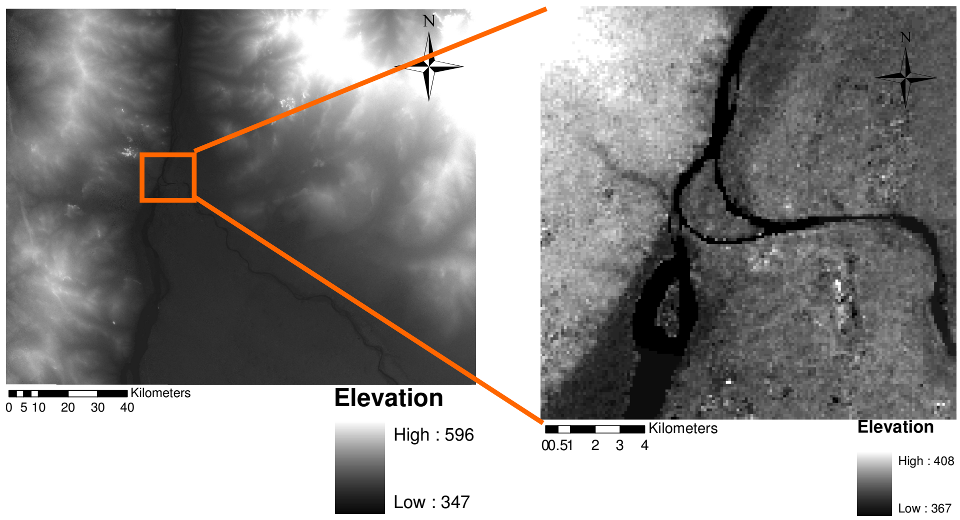

Figure 5.2: SRTM for the study area. (http://www.ambiotek.com/srtm).

5.1.3 The Arc Hydro Toolset

5.1.3.1 Introduction to Arc Hydro Tools

The Arc Hydro tools are a set of utilities developed on top of the Arc Hydro data model. The Arc Hydro Toolset is a suite of tools which facilitate the creation, manipulation, and display of Arc Hydro features and objects within the ArcGIS environment. Some of the functions require the Spatial Analyst extension. The tools are accessed through the Arc Hydro Tools toolbar, where they are grouped by functionality into five menus and six buttons. . The tools provide raster, vector, and time series functionality, and many of them populate the attributes of Arc Hydro features. ESRI, (2002c).

5.1.3.2 Steps to include Arc Hydro Tools in Arc map environment

ESRI, (2002b)

- Run the setup (setup.exe)
- Open ArcMap and load Arc Hydro tools
- Open ArcMap. Create a new empty map, and save it as ArcHydro.mxd (or any other name).
- Right click on the menu bar to pop up the context menu showing available tools. As shown in Figure 5.3.

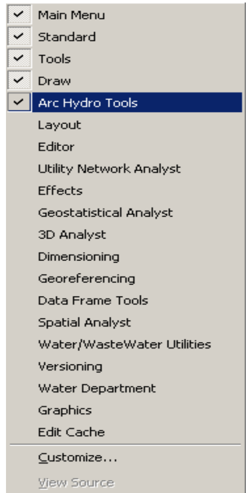

Figure 5.3 Active Arc Hydro Tools

- The Arc Hydro Tools toolbar is shown in Figure 5.4 .

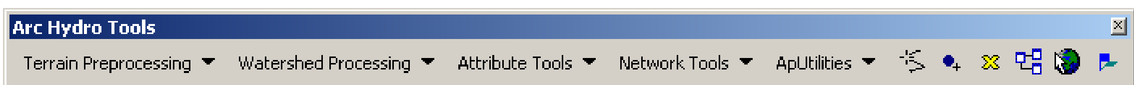

Figure 5.4 The Arc Hydro Tools toolbar

- Load the clipped SRTM map data
- Click on the  icon to add raster data.
- In the dialog box, navigate to the location of the data, select the raster file (e.g. "DEM") and click on the "Add" button.
- The added file is listed in the Arc Map Table of contents.
- Select Terrain Preprocessing | DEM Reconditioning. As shown in Figure 5.5 .

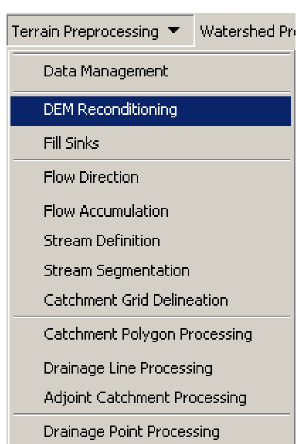

Figure 5.5 DEM Reconditioning

- Select the appropriate DEM and linear feature. The output is a reconditioned Agree DEM (default name AgreeDEM), as shown in Figure 5.6 .

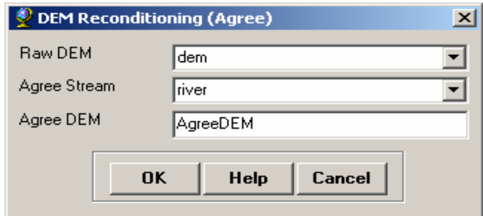

Figure 5.6 DEM Reconditioning (Agree)

5.1.3.3 Terrain Preprocessing

Tools in this menu deal with processing of Digital Elevation Model (DEM). It uses DEM to identify the surface drainage pattern. They are mostly used once in order to prepare spatial information for later use. All the steps in the Terrain Preprocessing menu should be performed in sequential order, from top to bottom

5.1.3.4 DEM Reconditioning (AGREE)

ESRI, (2002d) the DEM Reconditioning function (Terrain Preprocessing menu) modifies Digital Elevation Models (DEM) by imposing linear features onto them. It is an implementation of the AGREE method developed at the University of Texas at Austin in 1997. For a full reference to the procedure refer to the web link http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html

- The function needs as input a raw DEM and a linear feature class (river) that both have to be present in the map document.
- Names of DEM must be known in advance.
- The user needs to select an existing grid theme name that will be tagged with the "Raw DEM" tag at the end of the operation.
- Names of feature classes must be known in advance. Each feature class should have a unique name.
- The user needs to select an existing linear feature class that will be tagged with the "Agree Stream" tag at the end of the operation.
- The user needs to specify a grid name that will be tagged with the "Agree DEM" tag at the end of the operation. If the specified output grid already exists, the user is prompted whether to remove the existing dataset. If the user doesn't give a new name a default name will be used (Agree DEM). The user must be careful to use the new name DEM in the next process of embedding a new feature class. Make sure that the grids being created have unique names ESRI, 2002a)

After initiating the function, the user needs to enter three reconditioning parameters:

1. Vector buffer (cells) – this is the number of cells around the linear feature class for which the smoothing will occur. Figure 5.7 .
2. Smooth drop/raise – this is the amount (in vertical units) that the river will be dropped (if the number is positive) or the fence extruded (if the number is negative). This value will be used to interpolate DEM into the buffered area

(between the boundary of the buffer and the dropped/raised vector feature). (Figure 5.7).

3. Sharp drop/raise – this is the additional amount (in vertical units) that the river will be dropped (if the number is positive) or the fence extruded (if the number is negative). This has the effect of additional burning/fencing on top of the smooth buffer interpolation. It needs to be performed to ensure preserving the linear features used for burning/fencing.(Figure 5.7)

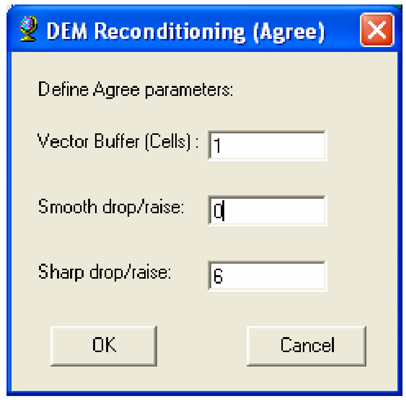

Figure 5.7 Define Agree parameters

The values used for the AGREE parameters depend on the nature of the DEM and the issues that are being resolved. In many cases, a trial and error approach is needed before satisfactory results are obtained

5.1.3.5 Creation of a shape file

A shape file had been created in order to lower the cells correspond to those cells.

- Data Management Tools > Feature Class > Create Feature Class > (In the output location create a folder , In out put feature class give a name, In Geometry type select POLYLINE.
- Editing > Start editing > (select the folder of the shape file) > Target select the name of the shape file > (Draw the shape file) as shown in **Error! Reference source not found.**.

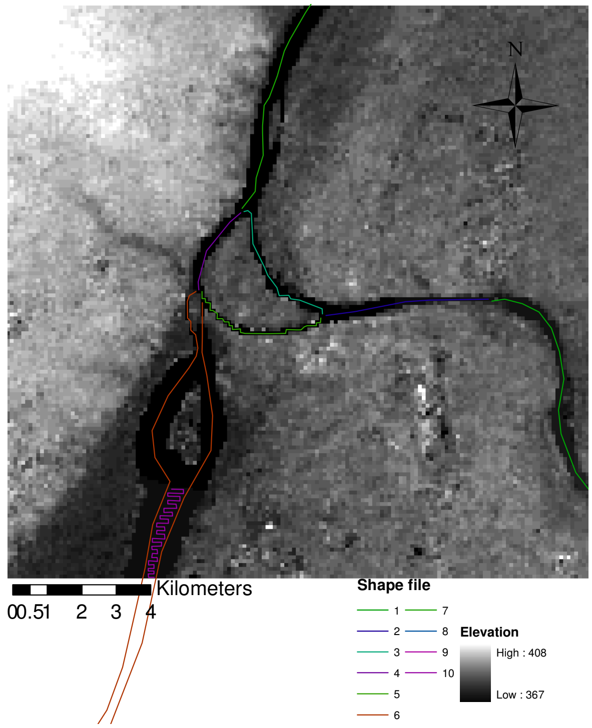

Figure 5.8: Creation of different shape files.

The result of the lowering grid will be as shown in **Error! Reference source not found.**.

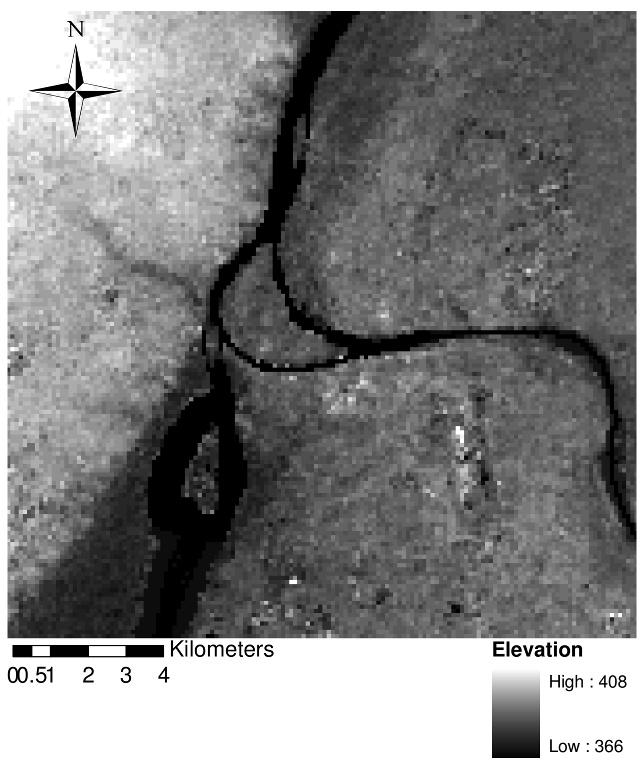

Figure 5.9: Lowering the DEM corresponding to the shape files by Arc Hydro Tools.

5.1.4 Preparation of topographical map:

For the purpose of this work and for good representation of the flood in Khartoum city a tedious work have been done to create a topographical elevation map for Khartoum. A PDF file from a free source was used to create an elevation map.
http://www.unsudanig.org/rco/data/flood/map/Map%201105%20Khartoum_Potential_Flood_Zones_2007_v2.pdf
A PDF file of Khartoum with a high resolution was downloaded from the above site. The image contains contour lines at the city. In addition, it shows the location of the street with the red lines. However the map doesn't show the elevation of the streets. Moreover, the map doesn't show the contour lines at the White Nile, Blue Nile and Main Nile. The production agency of this map is UN MIS Unit, the map produced at May 2007. The GPS Data, Roads, Airstrips, Hydrology and Infrastructure were made by UNMIS. Not all contents of this map have been field verified. In the future it's recommend that to verified this map with ground survey and GPS.
The picture in Figure 5.10 showed the topographical map.

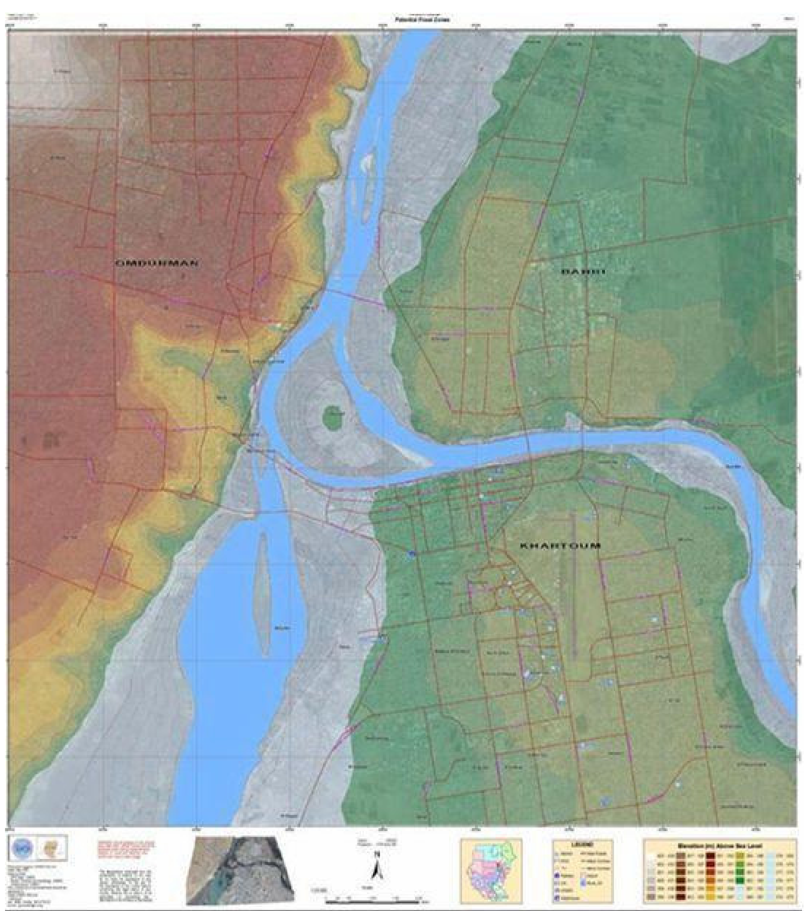

Figure 5.10 Image of topographical map

5.1.4.1 Add and georeference the map

- Download the PDF map from the free source site
- Save the image as a TIF file in order to import it GIS environment.
- Add the map 
- Then georefrenced the map as follow:
  - ➢ View> Toolbars> Georeferencing
  - ➢ Georeferencing> Fit to display> (from Google Earth select at least three points) > Click in the goerefereced point then to ungeoreferenced point>Press View link table (adjust the point to the desired one).
  - ➢ You have to be sure in the tag Layer the georeferenced layer is there

5.1.4.2 Create shape files for the digitized contour lines

- View> Toolbars> Editor
- Create a shape files as mentioned above with the desired name (Contour Lines).
- Open the attribute table> Option> Add filed> Give a name (Elevation) and select in the tag Type, short integer.
- Editor> start Editing> select the location of the shape file> sketch tool> (magnify the original map to digitize the contour well).
- Press Enter after digitize the whole contour (the contour should be digitized in one time)> in the attribute table in column Elevation (give the desired height)> Press save Edits.
- Continue with the other contour lines.

67 counter lines were carefully digitized as shown below in **Error! Reference source not found.**.

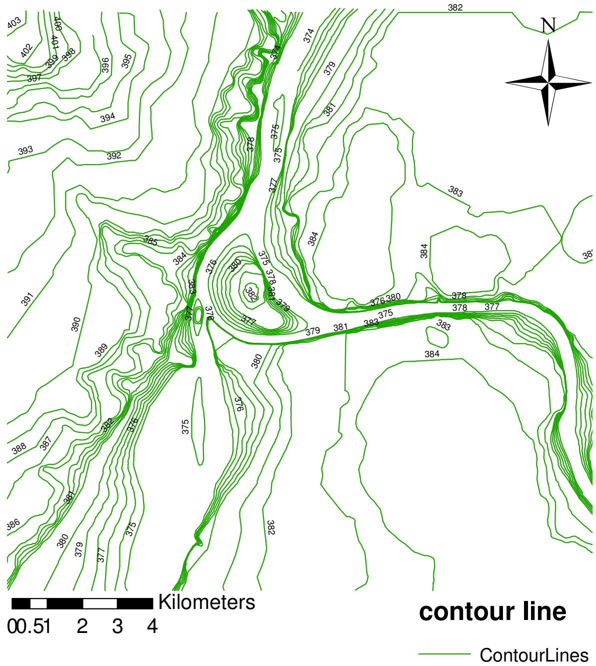

Figure 5.11: Digitized contour lines of Khartoum.

5.1.4.3 Convert the shape file to Tin

Triangular Irregular Networks (TIN) has been used by the GIS environment to represent surface morphology. TINs are a form of vector based digital geographic data and are constructed by triangulating a set of points. The points are connected with a series of edges to form a network of triangles. There are different methods of interpolation to form these triangles, such as Delaunay triangulation or distance ordering. ArcGIS supports the Delaunay triangulation method. (ESRI, 2006)

The resulting triangulation satisfies the Delaunay triangle criterion, which ensures that no vertex lies within the interior of any of the circum circles of the triangles in the network. If the Delaunay criterion is satisfied everywhere on the TIN, the minimum interior angle of all triangles is maximized. The result is that long, thin triangles are avoided as much as possible. (ESRI, 2006)

The edges of TINs form contiguous, non overlapping triangular facets and can be used to capture the position of linear features that play an important role in a surface, such as ridgelines or stream courses. Figure 5.12 shows the nodes and edges of a TIN (left) and the nodes, edges, and faces of a TIN (right).(ESRI, 2006)

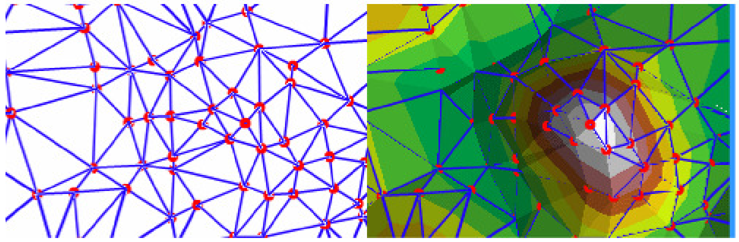

Figure 5.12: Nodes and edges of TIN on left, surface of TIN on right.

Because nodes can be placed irregularly over a surface, TINs can have a higher resolution in areas where a surface is highly variable or where more detail is desired and a lower resolution in areas that are less variable.

The input features used to create a TIN remain in the same position as the nodes or edges in the TIN. This allows a TIN to preserve all the precision of the input data while simultaneously modelling the values between known points. You can include precisely located features on a surface—such as mountain peaks, roads, and streams—by using them as input features to the TIN nodes.

The steps to convert the shape file to TIN are:

- View> Toolbars> 3D Analyst
- 3D Analyst> Create/ Modify TIN> Create TIN from Features> in tag Layers (tick Contour Lines)> in Height source in Setting for selected layer (select elevation.
- In Output TIN (select the location and the name of the file), the default name is tin.

The created TIN is as shown in **Error! Reference source not found.**

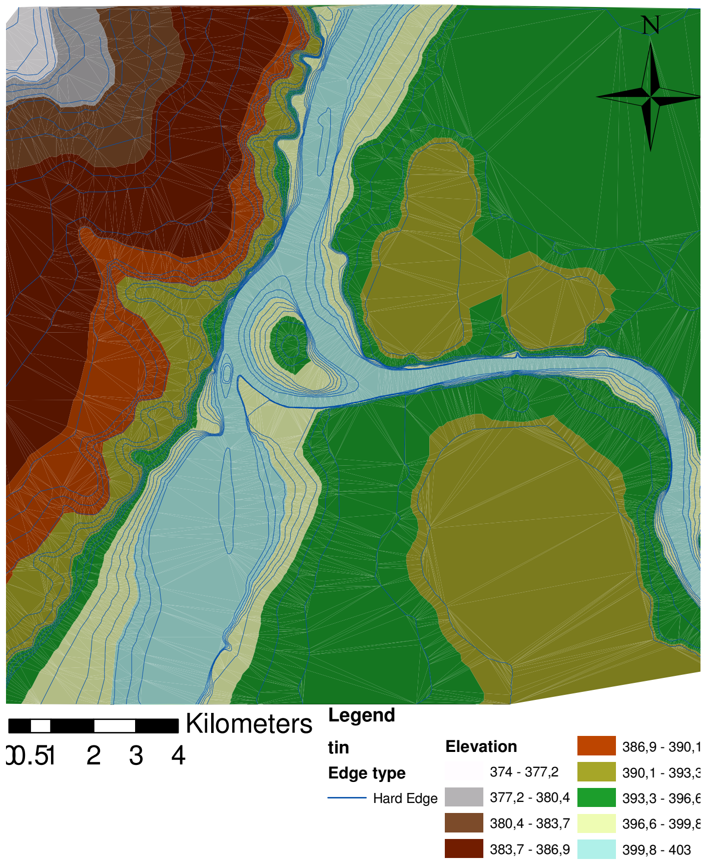

Figure 5.13: Convert the shape to TIN.

5.1.4.4 Create shape files for the digitized cross sections

At this stage we need to create a shape file for the cross sections of the rivers, and give it the exact elevation to embedded on the TIN map of Khartoum. The first step is to import and georeference a map which shows the location of the cross section from a report (UNESCO_Chair_for_Water, 2002) as shown in Figure 5.14.

The map shows intensive field and bathymetric survey work carried out by Hydraulics research station in May 2002 for UNESCO Chair in Water Resources for the project “River Nile Development within Khartoum Centre”. Twenty cross sections were surveyed bathymetrically and by land levelling. Moreover, thirteen auxiliary cross sections were bathymetrically surveyed; Figure 5.15 shows an example of an auxiliary cross section.

Figure 5.16 showed the overlying of the scanned map over the image of the topographical map

The next step is to create a shape file for the cross sections as follow:

- Create a shape files as mentioned above with the desired name (Cross sections).
- Open the attribute table> Option> Add filed> Give a name (Elevation) and select in the tag Type, short integer.
- Editor> start Editing> select the location of the shape file> sketch tool> (magnify the original map to digitize the cross sections; in this step you need a ruler to put the points at the same place).