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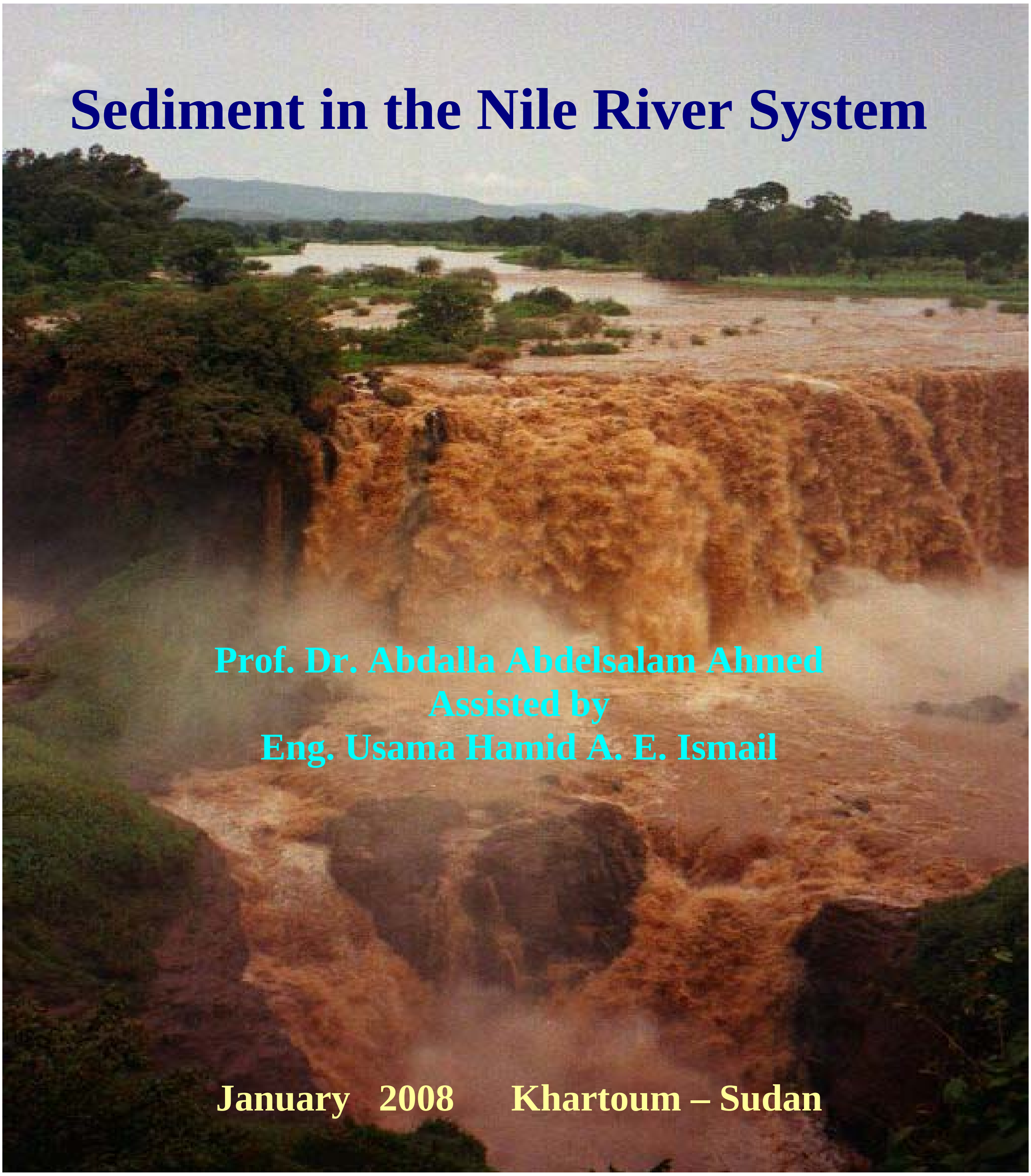

Sediment in the Nile River System

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Acknowledgment

The author and his assistant wish to acknowledge the support and encouragement of the International Sediment Initiative (ISI) of UNESCO-IHP and UNESCO Cairo Office (UCO) for providing us with this opportunity to carry out such an important study. We also want to thank all the UNESCO Chair in Water Resources staff for their continuous assistance in supplying valuable materials and some of the information presented in this study.

In particular we wish to thank Prof. Siegfried Demuth and Dr. Radwan Elweshah for their useful advance, encouragement and providing the suitable environment to complete this work. Finally we are very grateful to all those who helped us to complete this work, especially Eng. Ishraga Osman, Mr. Safe Zaroug and Ms Hala Mahgoub, who assisted in the graphs plotting and typing of the manuscript.

We hope that the study will be useful to all those who work in this field or related one, in particular the researchers and decision makers.

Executive Summary

Water of course is everyone’s business. Hardly a day goes by, when we don’t hear of flood, drought or/and pollution spill into surface waters or groundwater. Each of these issues has a direct or indirect impact not only on human security but on livelihoods and development. The topic of this study is related to all these aspects and more.

This report is the first attempt to study the Nile sediment at its regional level. It covers a wide range of issues related to sedimentation, with special emphasis on the Nile river system.

The main objective is to assess and understand the sedimentation process (erosion, transportation and deposition) in the Nile river system, and discuss its impact on the socio-economic development and the environment. Moreover, it serves as a practical reference in dealing with sedimentation and its related fields in the Nile Basin.

This study does not propose to cover all or even most of the complex subjects like sediment in the Nile river system, but rather to shed light on the issue as a first effort in this respect.

Sedimentation as an ecological and environmental phenomenon is increasingly affecting the sustainable development of human societies worldwide, especially in the Nile Basin.

The study is structured in nine chapters to cover in details the different aspects of the sediment in the Nile river system.

Chapter One gives a background and introduction to the Nile river system and the Nile Basin countries.

Chapter Two presents the Nile river hydrology with details on its seven sub-basins. It gives in geographically and in tabular form the water flows through the Nile system.

It should be realized that although the Nile is the largest river in the world, but not with much water. Its discharge is dwarfed by those of the Congo, the Niger, the Amazon, the Mississippi and the Mekong…etc.

Chapter Three explains the methods used to predict soil erosion and sediment yield, including the basic characteristics and monitoring. The chapter demonstrates the watershed degradation and sedimentation. It shows in details the rate of soil erosion and the portion that is delivered to the drainage system. The chapter documents on the erosion and land degradation in the ten countries of the Nile basin with emphasis on the Ethiopian Highland.

Chapter Four elaborates on the Nile bank erosion. The contribution of the bank erosion to the sedimentation process is explained. On the other hand, assessment of the extent, trend and impacts of the sand encroachment is also reported coupled with its influence on the agricultural land and the Nile water course.

Reservoirs play a significant role in human society, including flood control, water supply, power generation, irrigation, navigation, recreation…etc. In the Nile system, especially tributaries with sediment-ladder, reservoirs lose a certain percentage of their storage capacity due to sedimentation.

In Chapter Five, the subject of reservoirs sedimentation and its socio-economic and environmental impacts is expanded upon. Sedimentation in seven selected existing reservoirs in the Nile system is discussed. Rosaries reservoir presented as a case study. Trap efficiencies for almost all the existing reservoirs are presented. Sediment management and the control methods in these reservoirs are elucidated. This chapter shows in brief the extent of reservoir sedimentation problems.

Future dams and reservoirs on the Nile river system are described in *Chapter Six*. This includes those under construction and planned dams. The sedimentation process, which is going to face these reservoirs, is fairly discussed. The expected life span of each of reservoir is estimated.

As it is well known a considerable part of the Nile Basin is dry, therefore, irrigation is widely experienced. Irrigation networks suffer from sedimentation and management difficulties.

Chapter Seven explains the sedimentation problems in the irrigation canals and the interrelationship between the sediment and the aquatic weeds growth.

Chapter Eight deals with one of the most important issues, the socio-economic and environmental impacts of sedimentation in reservoirs and irrigation canals system. Gezira Irrigated Scheme experience, as the largest scheme in the world under a single management, is overviewed. Moreover, the effect of the sedimentation on the domestic water use plant treatment is explained. Therefore, water quality and sediment as pollutant, especially when dealing with safe drinking water, is highlighted.

Chapter Nine provides general concluding remarks on the study “Sediment in the Nile River System”. Finally the document presents the *References*

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List of Abbreviations

AHD	Aswan High Dam
B/C	Benefit/Cost
CA	Combined Account
DRC	Democratic Republic of Congo
D/S	Down Stream
EHRS	Ethiopian Highlands Reclamation Study
FAO	Food and Agriculture Organization
fd	Feddan
Fig	Figure
FRIEND	Flow Regime from International Experiment Network Data
FSL	Full Supply Level
GDP	Gross Domestic Product
GS	Gezira Scheme
ha	Hectare
HRS	Hydraulics Research Station
IA	Individual Account
ICOLD	International Commission of Large Dams
ICRAF	The World Agroforestry Centre
ISI	International Sediment Initiative
LVB	Lake Victoria Basin
masl	Meters Above Sea level
MOL	Minimum Operation Level
MoIWR	Ministry of Irrigation and Water Resources - Sudan
MoWR	Ministry of Water Resources - Ethiopia
MWRI	Ministry of Water Resources and Irrigation - Egypt
O & M	Operation and Maintenances
ppm	Parts per Million
RWS	Relative Water Supply
t/d	Tons per Day
t/yr	Tons per year
t/ha	Tons per Hectare
t/ha/year	Tons per Hectare per Year
t/km^2	Tons per Kilometer Square
$t/km^2/yr$	Tons per Kilometer Square per Year
PV	Present Value
UNESCO-CWR	UNESCO Chair in Water Resources
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
U/S	Up Stream
US $	United States Dollar
WB	World Bank
WHO	World Health Organization

Chapter One

Introduction

Sediment in the Nile River System

1.0 Background

Water is the most vital resource to support all forms of life on earth. It will remain essential for mankind survival and the future development of the world. Water is not evenly distributed over the world by season or location, i.e. global fresh water distribution is neither uniform in space nor in time. Some parts of the world are prone to drought making water scarce and precious commodity, while in other parts of the world it appears in raging torrents causing floods and loss of life and property. The last 50 years have seen remarkable developments in water resources and in particular agriculture, industry, and domestic consumption. Massive developments in hydraulic infrastructures have put water at the service of people. On the other hand, while the world population grew from 2.5 billion in 1950 to 6.5 billion today, the irrigated area doubled and water withdrawals tripled. Moreover, the Nile Basin with its majority situated in dry and semi-dry region is facing a similar fate of high water demand if not worse. The Nile River Basin, Fig. (1) is located between 4^0 S to 32^0 N & 23^0 to 40^0 E covering 10.3% of the African continent area. It is the sixth largest Basin in the world area-wide encompassing most of the northeastern Africa and incorporating ten countries in total (Burundi, D. R. Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda), with a combined population of about 325 million, about 170 million of them live within the boundaries of the Nile Basin, Fig. (1).

Fig. (1) Nile River Basin

The ten countries that share the Nile Basin include the world's poorest five countries, with annual per capital income of less than US$ 250. The gross national income of these countries is US$ 90 per capita (Burundi), US$ 110 (DRC, Ethiopia), US$ 190 (Eritrea) and US$ 210 (Rwanda). The life expectancy is 42 years in Ethiopia to 70 in Egypt. Child mortality rate per thousand is 210 in DRC to 36 in Egypt.

The Nile is considered the longest river in the world followed by the Amazon in South America. However the Amazon river brings seventy times the Nile annual flows. The Nile river runs 6700 km from its farthest sources of the headwaters of the Kagera river in Burundi and Rwanda to its delta in Egypt on the Mediterranean Sea. Many researchers believe Jinja at the Victoria Lake is the beginning of the Nile.

The Nile Basin setting is highly variable ranging from tropical rainforest at the equatorial lake region in the south to desert in the north. In the south, the wetland covers 100,000 km^2 where a variety of altitudes are found. They range from montage bogs and upland valley bottoms, through mid-level swamps and floodplains, down to riverine wetlands and eventually to the delta at below sea level.

The main branches forming the Nile Basin are; Blue Nile, White Nile, and Atbara river systems. The White Nile source is the equatorial lake where it begins as Victoria Nile passing through the Owen Falls Dam in Uganda to Lake Kyoga and then Albert Lake where is known as Albert Nile. Hence it continues into Sudan with the name Bahr El Jebel until its confluence with Bahr El Ghazal and Sobat rivers near Malakal, and from there on it is known as the White Nile river.

The Blue Nile (called Abbay in Ethiopia) and its main tributaries start from the Ethiopian Highlands. The Blue Nile originates from Lake Tana and joins the White Nile at Khartoum (the Capital of Sudan). North of Khartoum at Atbara City the Atbara river joins the Nile forming the Main Nile river.

The Nile river receives its flows from three main distinct watersheds; the Equatorial Lake Plateau in the south, the Sudd region in the center, and the Ethiopian Highlands in the east, Fig (2). From the confluence of Atbara river north of Khartoum to the Mediterranean Sea the Nile receives no effective inflow. On the other hand, although the catchment area of the White Nile is three times the Blue Nile, however, the Blue Nile contribution to the Nile flow is two times that of the White Nile.

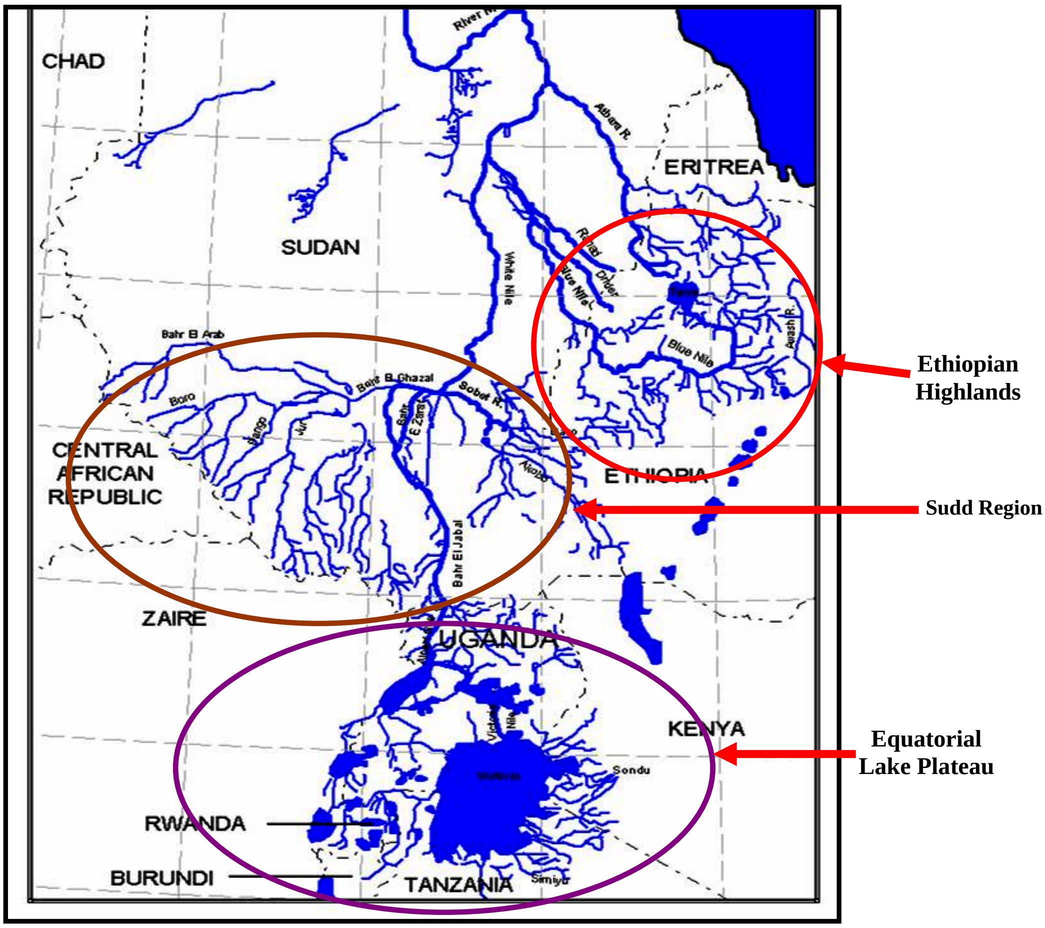

Fig. (2) The Three Main Watersheds of the Nile

1.1 Introduction

Sediment in the Nile is mainly originating from the Ethiopian Highlands with large quantities of eroded soil. This stems from frequently alternating dry–wet seasons coupled with agricultural over-utilization, overgrazing, wood cutting to sustain livelihood and housing. These are resulting in deforestation and loosening of the soil surface thus facilitating and accelerating water erosion. Therefore, it leads to land degradation in the upper land and loss of reservoir's capacities, flooding, blockage of hydropower inlets, irrigation canal's sedimentation and water quality degradation. The latter collectively summarizes the negative impacts of soil erosion from the Ethiopian Highlands on the downstream countries, e.g. Sudan and Egypt. On the other hand, the Equatorial Lake region, sediment results from soil erosion due to deforestation, human activities, and land use mismanagement. This leads to several negative impacts, e.g. threatening the overall biodiversity in the region in addition to the deterioration of the quality of water, especially in Lake Victoria. However, due to the swampy areas in the southern of Sudan besides, the several Lakes faced the White Nile through its way towards the north, most of the sediment deposits on those places. Hence the contribution of the White Nile to the Nile sediment discharge rate is less than 5%.

It has been proved that high erosion is usually associated with poverty where population overuses the available land resources to sustain their livelihood. The bulk of the Nile Basin's population lives on farming and animal resources. Therefore, they are heavily dependant on their land and water resources. The projected population's increase within the coming 25 years of the Nile riparian countries (325 million at present) is expected to be doubled (650 millions). Hence, an urgent need for a properly developed management system for the Nile Basin water resources is the only way ahead.

One of the main problems pressing and facing water resources management in the Nile Basin is sedimentation, which is the main reason behind carrying out this study.

Following the highly successful scientific gathering of the International Sediment Initiative Conference hosted by UNESCO Chair in Water Resources (UNESCO-CWR) in Khartoum, Sudan, 12 - 15 Nov. 2006, UNESCO-IHP Secretariat through the International Sediment Initiative programme asked Prof. Abdalla Abdelsalam Ahmed, the Director of UNESCO-CWR and Regional Coordinator of the Erosion and Sediment Transport Modeling Component of the FRIEND/ Nile Programme, assisted by Eng. Usama Hamid A. E. Ismail to produce a technical-scientific document discussing the sediment issues in the Nile river system. Therefore, the main objective of this report is to assess, evaluate and study the present situation of the sediment issues in the Nile Basin, and hence develop a better understanding of the sedimentation process in the Nile, which will lead to better mitigation measures and management. Moreover, is to highlight its impacts on the socio-economic and environmental conditions on the Nile Basin countries.

1.2 Statement of the Problem

The Nile river watersheds suffer severe land degradation and soil erosion due to extended dry seasons in some parts of the Basin, torrential rain and geological nature, bringing large quantities of sediment in the drainage systems. This leads to land degradation in the watershed and the upper lands, e.g. in Ethiopia Highlands in the east, and around upstream Lake Victoria in the south. At the same time, the sediment deposition in the reservoirs and irrigation systems downstream lead to serious reduction in reservoirs storage capacities and hence leading to hydropower generation problems, banks flooding and ultimately negatively impact on the socio-economic lives of the users, environment and ecosystem in general. Moreover, the sedimentation in the irrigation systems leads to water shortage and irritation management difficulties. On the other hand, sediment deposition on the bed of the river course raise the bed level, hence leads to flood risks and loss of human lives and their properties.

Chapter Two

Nile River Hydrology

2.0 The Nile Basin

The Nile Basin includes the river Nile system with its great and small lakes and swamps, dams and reservoirs, barrages, all its tributaries, and the mountain streams from which its water originates. Eight major sub-basins within the Nile catchment have been identified. The selection is based on watershed drainage divides and sub-basin characteristics and they are: - .

2.1 Lake Victoria Sub-basin

Lake Victoria is the world's second largest fresh-water lake and the largest in Africa, with a surface area of 68,800 km2, Fig. (3). The catchment area of Lake Victoria is divided between five African countries: Kenya, Tanzania, Uganda, Rwanda and Burundi. The Lake basin area covers 193,000 km^2 with Tanzania occupying 44 %, Kenya 22 %, Uganda 16 %, Burundi 7 % and Rwanda 11 %. The size of the Lake makes it a critical determinant of weather and climate in the region. Lake Victoria Basin has a population of about 30 million people of which approximately 25 million live in the three riparian states, i.e. about 30 % of the total population of the three countries (Kenya, Tanzania and Uganda).

The main rivers flowing to the Lake are Mara, Kagera, Mirongo, Grumeti, Mbalageti, Simiyu and Mori in Tanzania; Nzoia, Sio, Yala, Nyando, Kibos, Sondu-miriu, Kuja, Migori, Riaria and Mawa in Kenya and Kagera, Bukora, Katonga and Sio in Uganda. The Kagera river, which drains from Burundi and Rwanda and part of Uganda, is the single largest river flowing into the lake. However, rivers entering the lake from Kenya, which contains the smallest portion of the lake, contribute over 37.6 % of surface water inflows.

Three sources contribute to the net supply of Lake Victoria: the outflow of Kagera river, the direct precipitation on the lake surface and the direct runoff of the land portion of the catchment (many small rivers and streams).

The average annual precipitation is high and peaks in March–May and November–December. It amounts to 1,295 mm and is slightly higher over the Lake surface than over the adjacent land area. The rainfall varies considerably across the sub-basin from 688 mm in the southeastern part of the basin to more than 2,550 mm over the northwestern part of the lake.

Runoff is very much a function of the catchments climate, soil, land-use/land-cover, and topographic characteristics of the watershed and of the channel network. The yearly mean accumulated observed flow at Jinja is 30.97 billion m^3, which is equivalent to 130 mm of average runoff over the whole catchment. Thus, the runoff/rainfall ratio is 0.10 or, in other words, only 10% of the total rainfall over the sub-basin is observed at the Jinja outlet (the only outlet of Victoria Lake). This relatively low runoff/rainfall ratio, compared to Europe and North America, is caused by the high evaporation rate from the lake's surface and by the moisture losses in a bimodal precipitation regime. The outflow from Lake Victoria is controlled and therefore the yearly discharge or release at Jinja does not reflect the natural rainfall/runoff process in a particular year.

The lake itself possesses huge storage. A difference of one meter in the lake level represents the volume generated by more than two years of average outflow.

From the outflow of Lake Victoria at the Owen Falls dam, the White Nile flows into Lake Kyoga, then into Lake Albert and northwards into southern Sudan. The average annual precipitation over the area is 1,198 mm, and the average yearly flow at Mongalla the outlet of Albert lakes amounts to 26.5 billion m^3, Fig. (4).

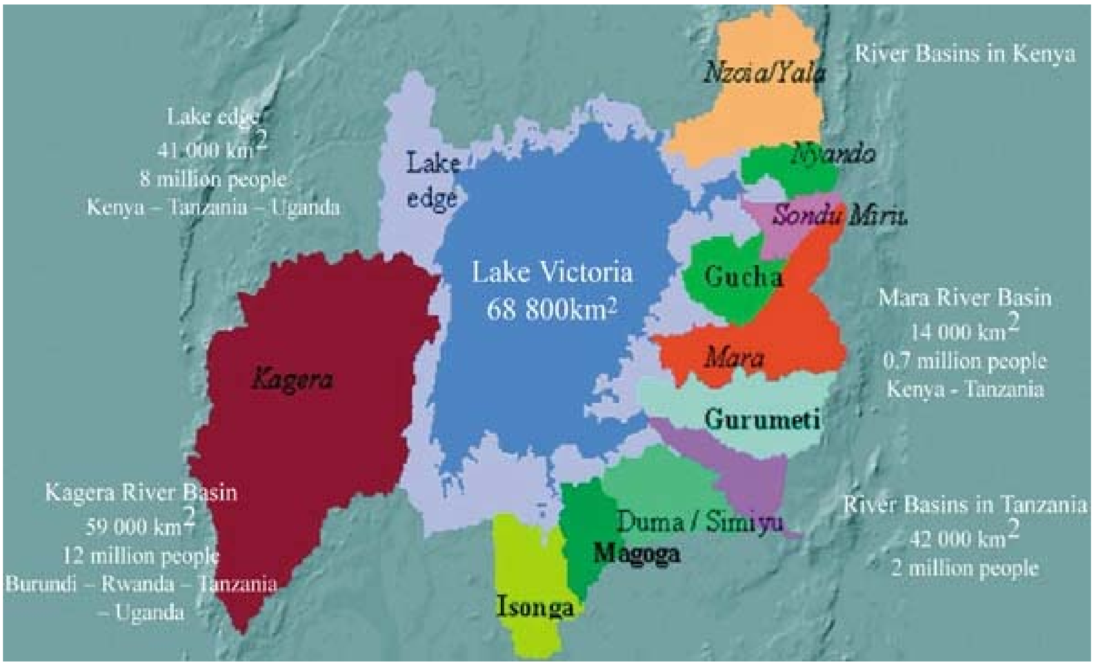

Fig. (3) Lake Victoria Sub-Basins

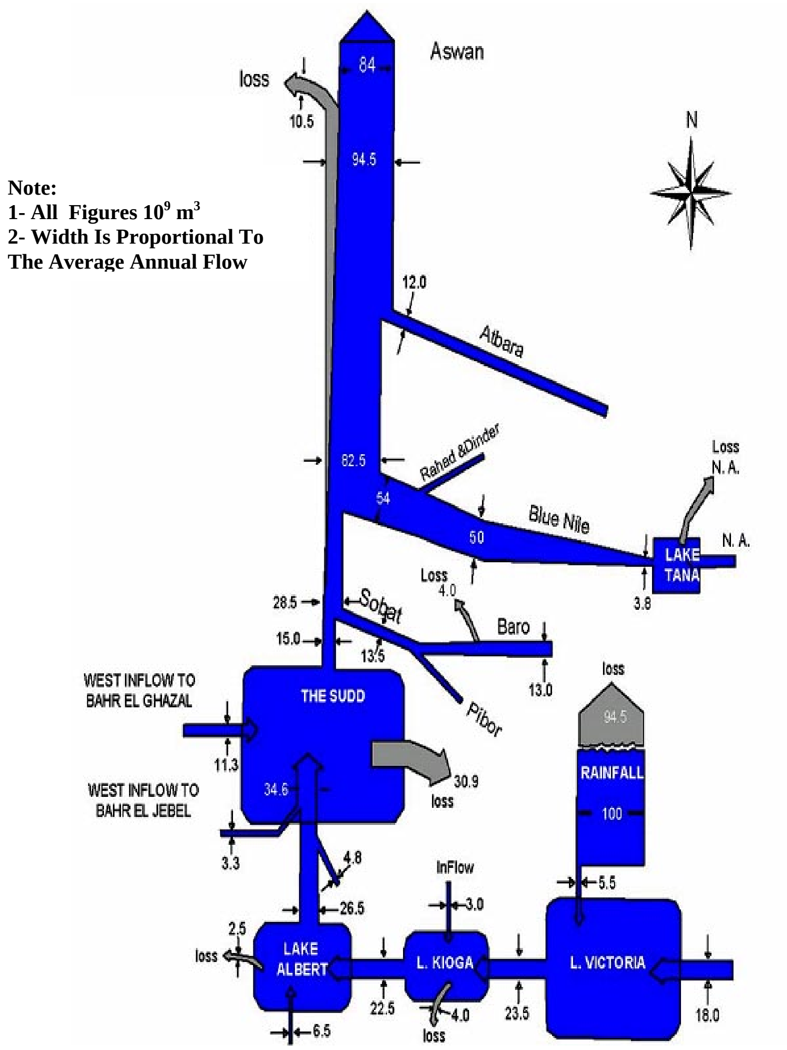

Fig. (4) Schematic Diagram of the Nile River Natural Flows

2.2 Sudd Sub-basin

Within Sudan to the north from Mongalla, the White Nile is known as the Bahr el Jebel and flows into a vast complex of channels, lakes and swamps in an enclosed basin. The entire area is very flat. From Mongalla to Malakal, the slope of the land averages only 10 cm/km.

The watershed area is about 139,425 km^2. The average annual precipitation over the area is 923 mm with a peak of over 1,470 mm in the southern part of the basin. Rainfall intensity decreases to the north where the annual average does not exceed 760 mm. Precipitation falls mostly in one season from April to October. This coincides roughly with the river flood period when the area is permanently flooded (swamps).

A comparison of the historical inflow data in the Sudd area (45.9 billion m^3) and inflow data at Malakal (15 billion m^3) shows losses of 30.9 billion m^3 due to evaporation. Taking into account that the Sobat river contributes on average 13.5 billion m^3 of water annually to the flow at Malakal, it can be easily concluded that more than 34 billion m^3 of water is lost, mostly by evaporation, evapotranspiration, and percolation, in spite of the local precipitation over the sub-basin itself.

2.3 Bahr Al-Ghazal Sub-basin

This sub-basin, with an area of about 330,375 km^2, consists of a number of tributaries that run from the border of the D.R. Congo basin to the Nile. The peak of rainfall intensity in the south- western is about 1,550 mm and decreases to 500 mm toward the Northeast. Hence, the average annual precipitation over the entire area is in the order of 970 mm.

In such a large area of very low slope, nearly all the basin runoff and precipitation evaporates, therefore only about 0.5 billion m^3 (out-flow from Lake No) leaves the basin annually.

2.4 Sobat Sub-basin

The Sobat river is a result of two main tributaries (i) Baro river from the Ethiopian Highlands, and (ii) Pibor river from southern Sudan and northern Uganda. However, one of the main tributaries which join the Pibor river is Akobo river (originating from Ethiopian Highlands).

The area of this sub-basin is about 186,275 km^2. The rainfall intensity in Baro basin is about 2,000 mm while in both Pibor and Akobo basins is far less (slightly over 300 mm). The average annual precipitation over the entire sub-basin amounts to 1,057 mm. The Baro river is the larger of the two and is highly torrential and seasonal. Many of the tributaries of the Sobat river tend to overflow and form a large swamps area when they reach the flat plains of Sudan; this includes the Marchar Marshes, Fig. (5). The water losses are estimated as 30% for Baro basin and 14% for Pibor basin.

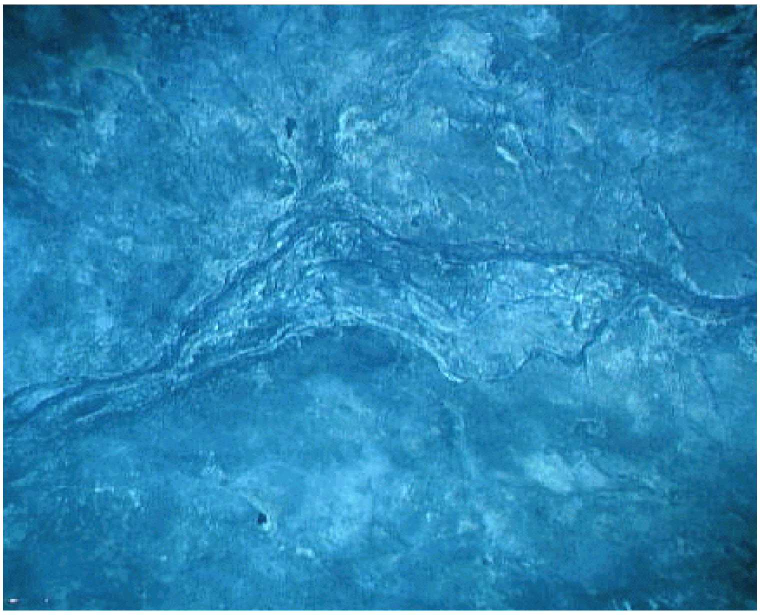

Fig. (5) The Marchar Marshes

2.5 White Nile Sub-basin

On the stretch from Malakal to Khartoum, the White Nile flows into increasingly semi-arid conditions. On average, there are 2.0 billion m^3 water losses due to evaporation as measured at Malakal. Some 700 km downstream Malakal the Jebel Aulia dam was built (40 km upstream of Khartoum) in 1937 by the Egyptian to store water for their uses, which added about 2.5 billion m^3 to the evaporation losses along this stretch. Jebel Aulia dam was handed over to the Sudanese in the seventies of the last century after completion of AHD. At Khartoum, the White Nile joins the Blue Nile to form the Main Nile.

2.6 Blue Nile Sub-basin

Four main small rivers run into Lake Tana, one of them is the little Abbay river (Gilgel Abbay), which is considered as the source of the Blue Nile. Tana Lake is the largest lake in Ethiopia. It is 78 km long, 67 km wide, 15 m max. depth and with average depth of 8.0 m. Lake Tana catchment area is estimated to be 16500 km^2 while its surface area is 3600 km^2. However, the contribution of Lake Tana to the Nile is less than 10 % of the Blue Nile annual flow. The Blue Nile (locally in Ethiopia called Abbay) exits from the southeastern corner of Lake Tana and cuts a deep gorge first south then westwards. Along the way it is joined by a number of tributaries: Beshilo, Weleka, Giemma, Beles, Muger, Guder, Finchaa, and Didessa from the east and south; and the Birr, Fettam, and Dura from the north and Dabus from the west, Fig (6). The Blue Nile runs 900 km down through the Ethiopian Highlands just before crossing the frontier, then the river enters into the clay plain of Sudan, through which it flows over a distance of about 735 km to Khartoum. The distance from Lake Tana to Khartoum is 1635 km, which is considered approximately the length of the Blue Nile.

The highest point in Lake Tana is something slightly above 1800 masl to enter Sudan at a level of 490 masl at the border of the two countries, i.e. with a gradient of approximately 1.5 m/km, which is considered very high slope. However, if we consider the whole reach from the highest point in the Ethiopian Highlands (4250 masl) up to confluence at Khartoum (350 masl), the difference in levels is tremendous. These values indicate that the slope before Lake Tana might be more than 20 m/km in average or in some part downstream Lake Tana exceeds more than 100 m/km in the gorge area, which is believed to be beside others one of the main reasons, behind the high soil erosion in the Ethiopian Highlands. However, on the contrary the average slope of the river from the Ethiopian frontier to Khartoum is about 15 cm/km, which is considered relatively flat.

The Dinder and Rahad rivers are the main tributaries of the Blue Nile. They rise to the west of Lake Tana (Ethiopian Highlands) and flow westwards across the border joining the Blue Nile below Sennar dam. They are seasonal streams and generally cease to flow during the dry season. They are nearly equal in length, about 750 to 800 km. The effective catchment areas of Dinder and Rahad are about 16000 and 8200 km^2 respectively. The average annual flows of the Dinder River is about 3.0 billions m^3, while the Rahad river is about 1.0 billion m^3, i.e. the annual average flow of Dinder and Rahad rivers is estimated as 4.0 billion m^3.

The Blue Nile basin, up to Khartoum including the Dinder and Rahad sub-basins, has an area of 324,530 km^2, and is characterized by highly rugged topography and considerable variation of altitude ranging from about 350masl at Khartoum to over 4250 masl in Ethiopian Highlands. The area of the Blue Nile catchment is about 141,900 km^2. Fig. (7), shows the Blue Nile river basin and the main tributaries inside Ethiopia and Sudan. The average annual precipitation over the Blue Nile sub-basin is 1,346 mm, making it the highest among all the sub-basins of the Nile. The lowest rainfall is recorded over the eastern part of the sub-basin where the average annual precipitation does not exceed 800 mm, where the highest values (exceeding 1,900 mm) are found over the southern part of the catchment. The average runoff/ rainfall rate is estimated to be 20 %.

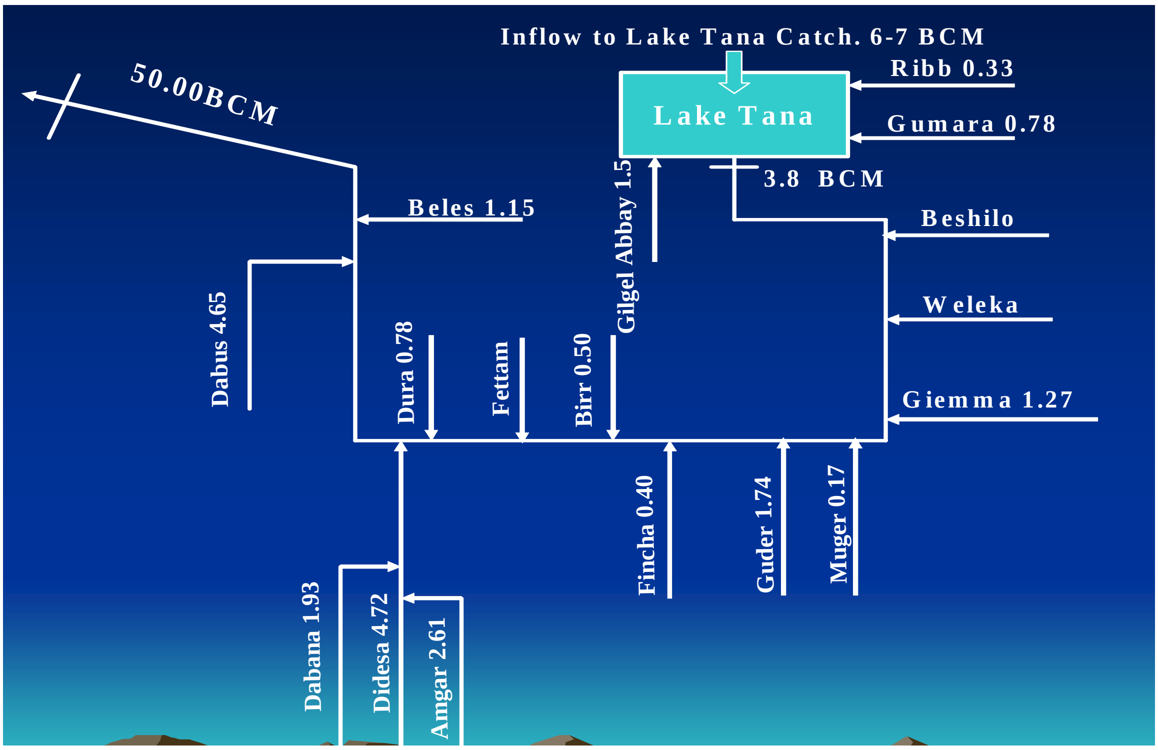

Fig. (6) Blue Nile Flows and their Tributaries

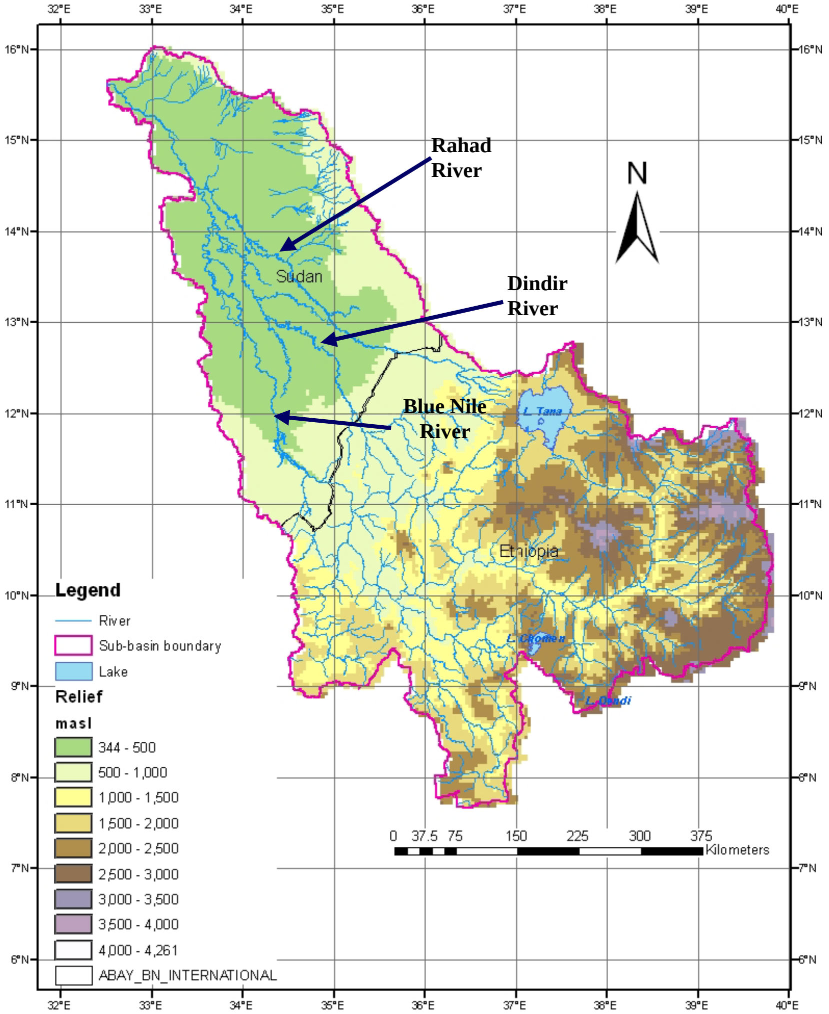

Fig. (7) Blue Nile Basin

2.7 Atbara River Sub-basin

The Atbara river is the most northern tributary to join the Nile river. Its headwaters originate in the north-western Ethiopian Highlands. The nature of the river is extremely torrential. Fig. (8), shows Atbara River basin and its main tributaries (Upper Atbara and Setit) and Khashm ElGirba dam reservoir. The entire Atbara sub-basin is quite large. It is estimated as 166,875 km^2. The average annual precipitation over the area is 553 mm, the lowest among the Nile sub-basins. The relatively high value of more than 1,300 mm of annual rainfall over the Ethiopian Highlands decreases to less than 90 mm downstream at the junction of the Atbara river with the Main Nile. The average runoff/rainfall rate is estimated to be 12%. The majority of the river discharge is derived upstream of the Khashm ElGirba reservoir which was constructed in 1964.

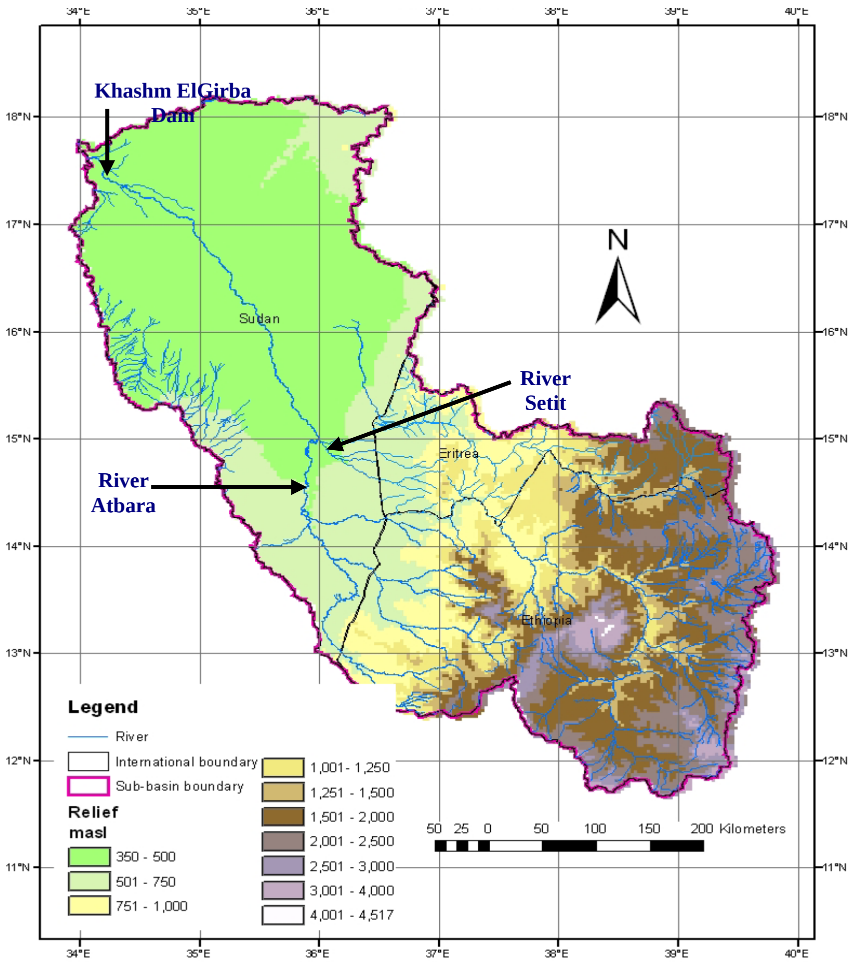

Fig (8) Atbara River Basin

2.8 Entire Nile Bain

The entire Nile Basin area is simply the sum of all the sub-basins mentioned above (2.1-2.7). Areas in which runoff are diverted to other river basins and arid areas where there is no rain at all are not counted, the entire Nile Basin corresponds to 1,527,500 km^2. However, in the literature the total area of the Nile Basin is estimated as 3,112,369 km^2, Table (1), which includes areas without rainfall (i.e. has no runoff contribution to the Nile flow). The entire Nile catchment runoff/rainfall coefficient is estimated as 5.5%, which is very small compared to other international rivers and even to the African ones (e.g. Congo Basin, Niger Basin). The average annual flow of the Nile river is estimated to be 84 billion m^3 as measured at AHD. The latter figure (84 billion m^3) is the average flow of the Nile for the period (1905 – 1959). This value is the one on which the Nile Waters Agreement between Sudan and Egypt was based. However, Fig. (9), the long term average flow of the Nile at Dongola gauging station is 73.0 billion m^3 annually. Fig. (10) also shows the average flow at AHD reservoir is 70.0, billion m^3 in the same period. The latter figure is supposed to cater for Egypt's share in the Nile waters according to the 1959 Agreement, i.e. with access of about 4.5 billion m^3 in average annually for the last 45 years, considering the share of Egypt is 55.5 billion m^3 and 10.0 billion m^3 for evaporation annually from AHD reservoir.

Table (1) Areas and Rainfall by Country in the Nile Basin

Country	Country total area (km2)	Country Area within the basin (km^2)	As % of total area of basin (%)	As % of country area (%)	Basin average annual rainfall in (mm)		
					Min.	Max.	Mean
Burundi	27834	13260	0.4	47.6	895	1570	1110
Rwanda	26340	19876	0.6	75.5	840	1935	1105
Tanzania	945090	84200	2.7	8.9	625	1630	1015
Kenya	580370	46229	1.5	8.0	505	1790	1260
Zaire	2344860	22143	0.7	0.9	875	1915	1245
Uganda	235880	231366	7.4	98.1	395	2060	1140
Ethiopia	1100010	365117	11.7	33.2	205	2010	1125
Eritrea	121890	24921	0.8	20.4	240	665	520
Sudan	2505810	1978506	63.6	79.0	0	1610	500
Egypt	1001450	326751	10.5	32.6	0	120	15
Nile Basin	8889534	3112369	100.0	35.0	0	2060	615

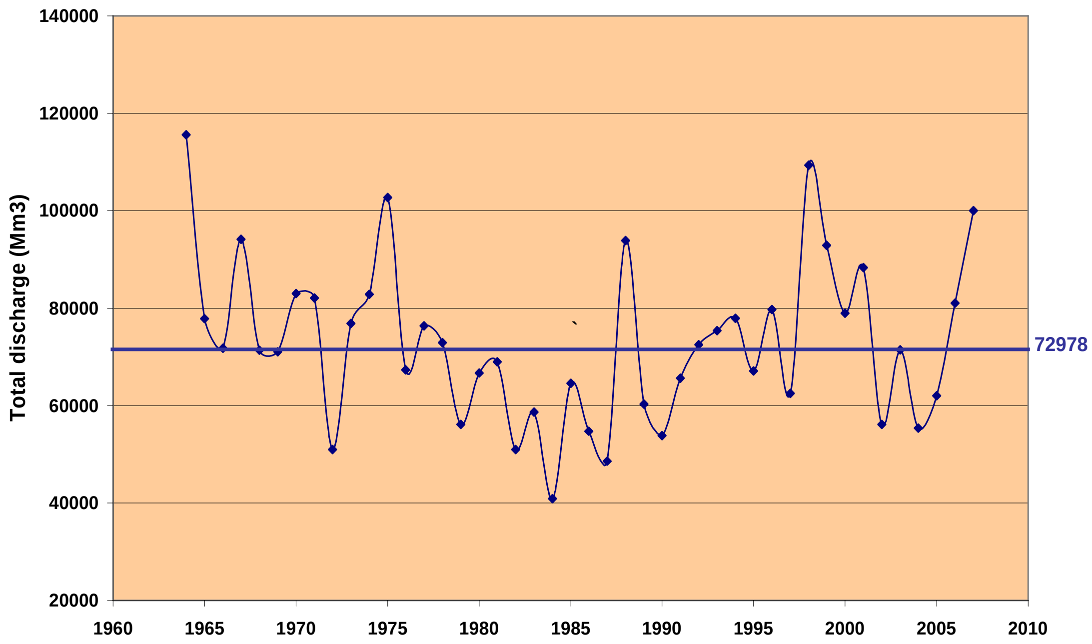

Fig. (9) The Nile Long Term Average Flow at Dongola

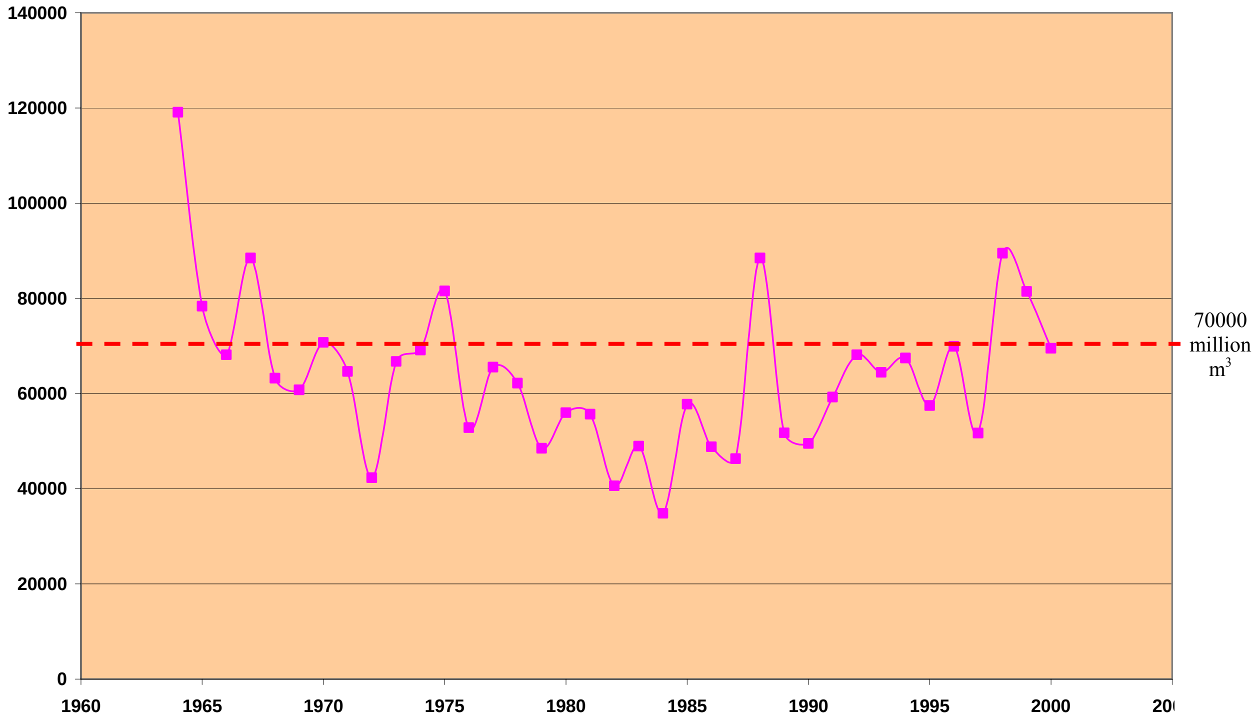

Fig. (10) Average Flow at AHD Reservoir

2.9 Water Flow through the Nile System

Catchment of the Nile can be divided into three distinct regions according to the provenance of the water and its hydrological regime Ahmed and ElDaw, (2004), Fig (2). Fig (4) shows the schematic diagram of the natural flow of the Nile river. Fig (11) gives the hydrographs of the main tributaries of the Nile river system as described by Ahmed and ElDaw, (2004). According to them and since the Nile river receives no effective inflow from the confluence of Atbara river north to the Mediterranean, the three main watersheds are defined as follows:-

(i) The Southern watershed draining the Equatorial Lakes plateau,
(ii) The Central watershed draining the Sudd region, and
(iii) The Eastern watershed draining the Ethiopian Highlands.

The total estimated annual inflow entering Lake Victoria from stream flow and rainfall is 118 billion m^3, while the evaporation is estimated to be 94.5 billion m^3, leaving only 23.5 billion m^3 to flow down the Nile river. About 86 % of total water input falls as rain on Lake Victoria itself. The average annual rainfall in the Lake area ranges between 886 mm to 2609 mm. Evaporation losses account for 80% of the water leaving the Lake.

The Nile river is the only surface outlet from the lake, with an annual outflow of 23.5 billion m^3. The waters originating from Lake Victoria provide hydropower through its only outlet, the Nile river, at Owen Falls dam in Uganda and other power plant downstream (Bujagali dam). The hydropower generation from the two plants is 260 Mw, part of which is exported to Kenya. Hence, the water that is draining the Equatorial Lakes enters the swamp area (Sudd region) in Southern Sudan. In this region, several other rivers also contribute water and sediment to the Nile river. The latter as a watershed was recognized for the first time by Ahmed and ElDaw (2004) to play an important role in the future development of the Nile Basin, and was defined as the Central Watershed. In the Sudd region inside Sudan, evaporation losses are estimated to be around 30.9 billion m^3, leaving only 15 billion m^3 to flow into the White Nile system.

The White Nile which transports water from the Central Watershed leaves almost all the sediment to be deposited in the Sudd area. The White Nile contributes a relatively constant flow to the Nile river from the Equatorial lakes through the swamps of the Sudd. This is in strong contrast to the rivers draining the Ethiopian Highlands watersheds (Blue Nile, Atbara and Sobat).

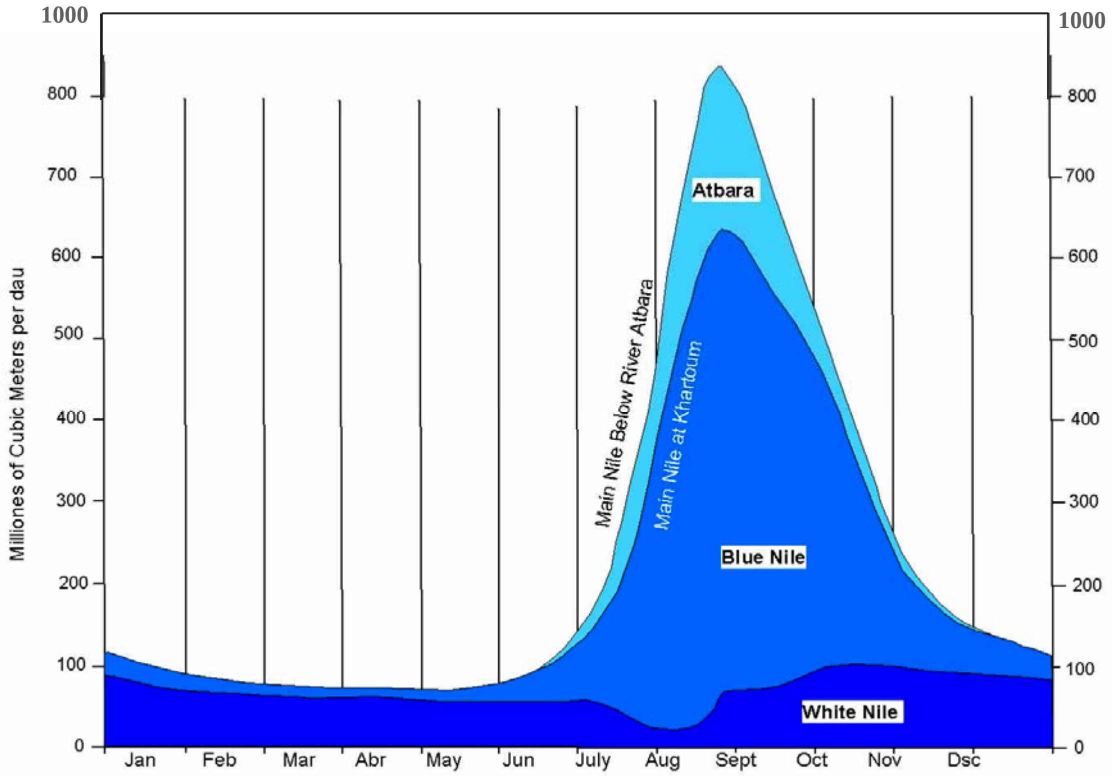

Fig (11) Hydrograph of the Blue Nile, White Nile and Atbara Rivers

Fig. (12) shows the hydrograph of the annual flows of the White Nile for the period (1960 – 2007) where the average annual flow is estimated to be 31.8 billion m^3. The annual flow is almost around the average, except for 1965 (47 billion m^3) and 1966 (38.9 billion m^3). However, the MOIWR official value for the White Nile annual average main flow is considered as 29.0 billion m^3.

On the other hand, the Blue Nile flows through the Sudanese-Ethiopian boarder north from humid to semi-arid conditions. Although there is a reasonable additional runoff between the boarder and Roseires dam (about 110 km), however, usually little additional runoff north of Roseires is taken into consideration with the exceptions of the two tributaries (Dinder and Rahad rivers), which join the Blue Nile downstream the Sennar dam. The average annual discharge of the Blue Nile at the Sudanese-Ethiopian boarder is known in the literature to be about 50 billion m^3, however, from Fig. (13a) the Blue Nile long term average (1920 – 2006) is 48.86 billion m^3, while Fig. (13b) reflects the long term average of 2.7 and 1.1 billion m^3 for Dinder and Rahad rivers flows respectively**.** The runoff/rainfall ratio over this basin is 20%, which is also the highest among all the other sub-basins in the Nile Basin.

Fig. (14) gives the average flow of Atbara river in the period (1983-2000). The average annual inflow is found to be 13.08 billion m^3 which is confirmed the already known 12 billions m^3 as a long term flow average for Atbara river. The runoff/rainfall ratio over Atbara basin is slightly less than 15%. In this period the minimum flow recorded in 1984 (4.9 billion m^3) and the higher flow recorded in 1998 (26 billion m^3) which is more than double the average annual flow.

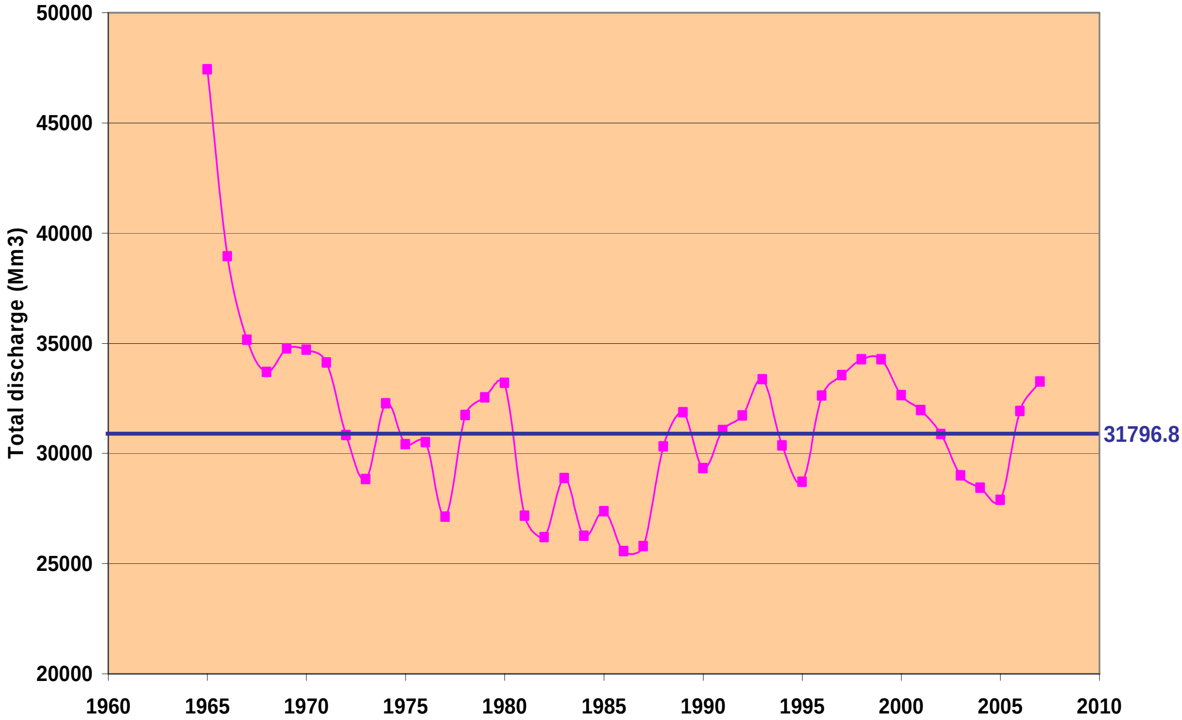

Fig. (12) White Nile Annual Flow Hydrograph

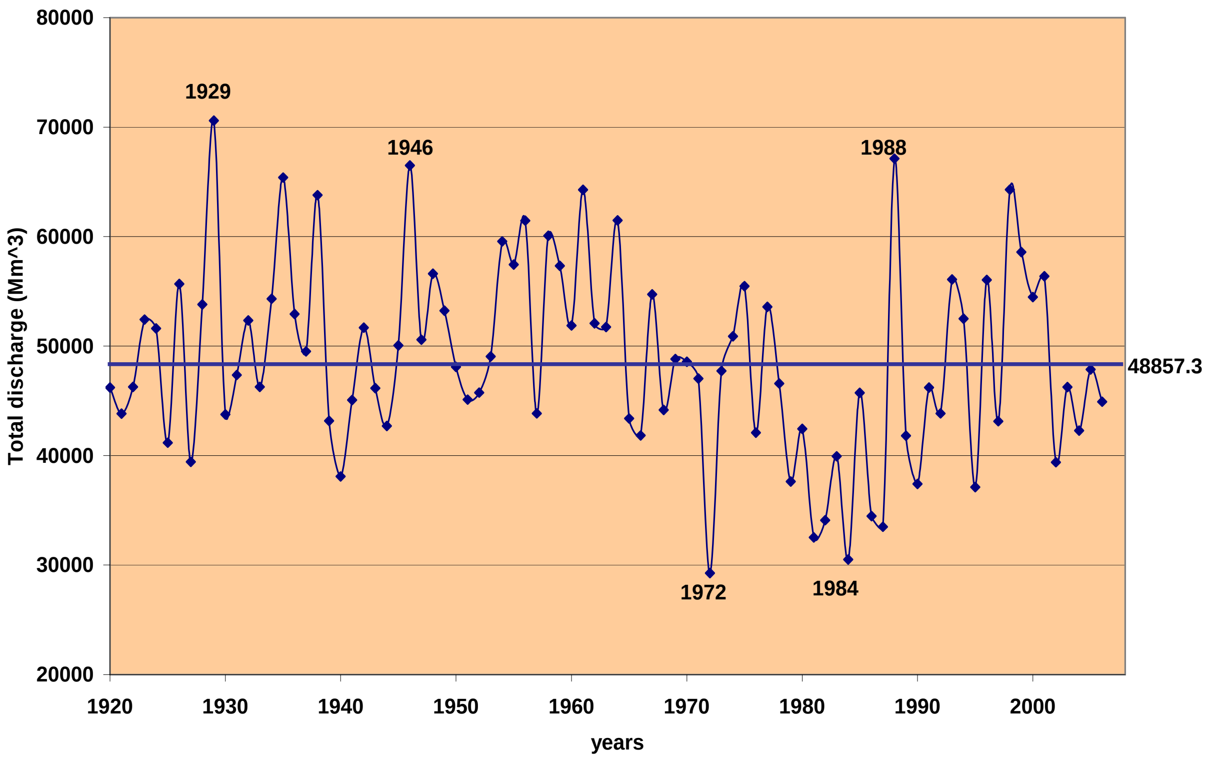

Fig (13a) Blue Nile Hydrograph (1920 – 2006)

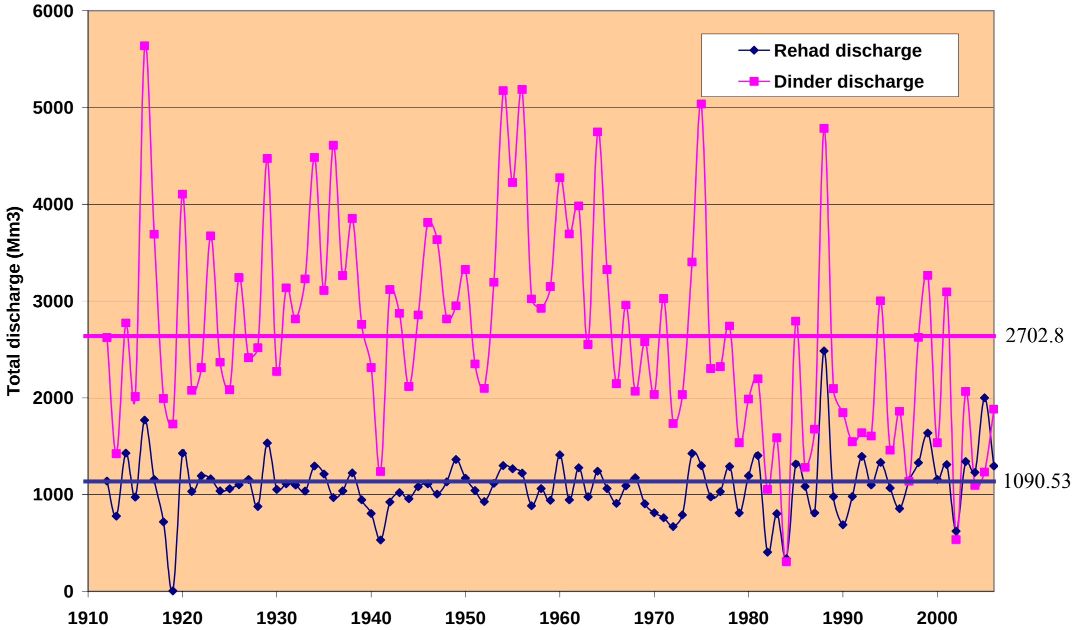

Fig. (13b) Dinder and Rahad Rivers Average Flow (1912 – 2005)

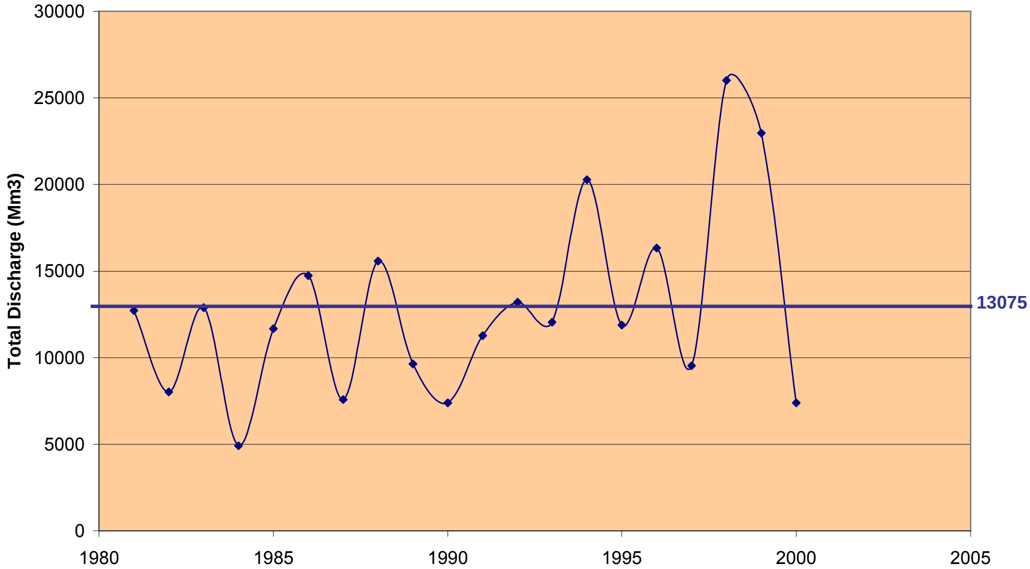

Fig. (14) Atbara River Average Flow (1983-2000)

Chapter Three

Soil Erosion and Sediment Yield

3.0 Methods for Predicting Soil Erosion and Sediment Yield

As a result of runoff from rainfall or snowmelt, soil particles on the surface of a watershed can be eroded and transported through the processes of sheet, rill and gully erosion. The loss of topsoil due to surface erosion not only can cause environmental problems, but it can also have adverse impacts on the agricultural productivity of a watershed. Once eroded, sediment particles are transported through a river system and eventually deposited in reservoirs, lakes, or at sea. Engineering techniques used for the determination of erosion rate of a watershed rely mainly on empirical methods, computer model simulation, or field survey.

Sediment yield is the end product of erosion by action of water, wind, ice and gravity. The factors that determine a watershed, sediment yield can be summarized as follows.

- Rainfall amount and intensity.
- Soil type and geologic formation.
- Ground cover.
- Land use.
- Topography.
- Up land erosion rate, drainage network density, slope, shape, size and alignment of channels.
- Runoff.
- Sediment characteristics (grain size, mineralogy, etc.)
- Channel hydraulic characteristics.

Most of empirical approaches for the estimation of erosion are based on one of the following methods.

- Universal Soil Loss Equation (USLE) or its modified versions.
- Sediment yield as a function of drainage area.
- Sediment yield as a function of drainage characteristics.

However all the developed empirical equations based on the above methods are either confined to the local watershed from where they had been developed or they give a rough estimation of the quantity of the sediment yield.

Aerial photographs can be used to make qualitative, or with calibration, quantitative assessments of soil erosion rates. However, aerial photograph to assess soil erosion is subjective and has been superseded by other methods. The most widely used empirical equation for the prediction of soil erosion is the Universal Soil Loss Equation (USLE), Wischmeier and Smith (1965), which estimates erosion rates by multiplying a number of factors, including rainfall intensity, soil erodability, slope length, ground cover and the presence (or absence) of soil conservation structures. Several empirical functions can predict sediment yields. These empirical functions are based on catchment area, slope, altitude, rainfall, runoff, temperature, plus factors indicating vegetation cover and proneness to erosion. Milliman and Syvitski (1992) successfully correlated sediment yields with catchment area and topographic factors using seven topographic categories. A number of methods are used in the Nile system catchments. One of the simple methods to predict the sediment yield ($t/km^2/yr$) is through converting sedimentation rates to catchment sediment yield. In such a method sediment trap efficiency of the dam reservoir has been taken into consideration using Brune (1993) relationship (dam reservoir capacity / inflow). Moreover, proper density of the deposited sediment is necessary (usually 1.1 to 1.5 t/m^3) depends on the deposits consolidations.

Sediment Yield (t/km^2/yr)
= Annual Sedimentation Rate (m^3/yr) x Sediment Density (t/m^3)

3.1 Nile Watersheds Degradation and Sedimentation
It is widely reported that land degradation occurs in the watersheds of the Nile river. The land degradation in watersheds usually starts in high altitude, where many factors naturally and artificially create the enabling environment resulting in soil erosion. In the Ethiopian Highlands as well as in the Equatorial Lakes, their watersheds face growing stress from economic development, increasing human populations and often wasteful use of natural resources like wood cutting for more housing, mining, timber for energy needs, over grazing, …etc.
Watersheds degradation is believed to be the main cause of sedimentation in general and in the Nile Basin system in particular. The causes of sediment in the watershed can be summarized as follows:-

- Removal of forests or other vegetation sharply reduces water retention and increases erosion, resulting in reduced water availability in dry seasons and more sedimentation downstream.
- Absence of trees provides passive effects on shrubs which lost shelters and some times die out under burning sun.
- Charges in river flow, sediment and pollutant loadings resulting from activities for inland degrade downstream ecosystem.

The Nile Basin watersheds are seriously suffering from accelerated soil erosion. This means that valuable fertile soils are lost from the land, where they are needed and deposited in the water system and ultimately in the lakes e.g. Victoria Lake Swamps in the Southern part of Sudan, in the reservoirs and irrigation systems.

3.2 Sediment Process
The process of sedimentation usually happens in the following stages:-

i- Erosion,
ii- Entrainment (drawing of particles into fluid),
iii- Transportation,
iv- Sedimentation/Compaction (deposition)

The processes are highly complex. The detachment of particles in the erosion process occurs through the kinetic energy of raindrop impact, or by the flowing water. Once a particle has been eroded it must entrain before it can be transported away. Both entrainment and transport depend mainly upon the weight, shape, size and forces exerted on the particles by the flow. Fig. (15) gives a schematic chart of the sediment processes in a simple form. Deposition occurs when the forces are diminished enough leading to a reduction or cessation of transport. Therefore, when a river flow enters a reservoir, its velocity and transport capacity are reduced and its sediment load is eventually deposited. For example the amount and rate of deposition in a reservoir are determined mainly by:-

- Detention storage time
- The shape of the reservoir
- The operating procedure of the reservoir

The depositional pattern usually starts with the coarser material depositing towards the reservoir headwater, while finer sediment is transported further into the reservoir. The aggradations continues more and more until a delta is formed, as it happens in Roseires reservoir in the Blue Nile, Plate (1), and AHD reservoir in the Main Nile.

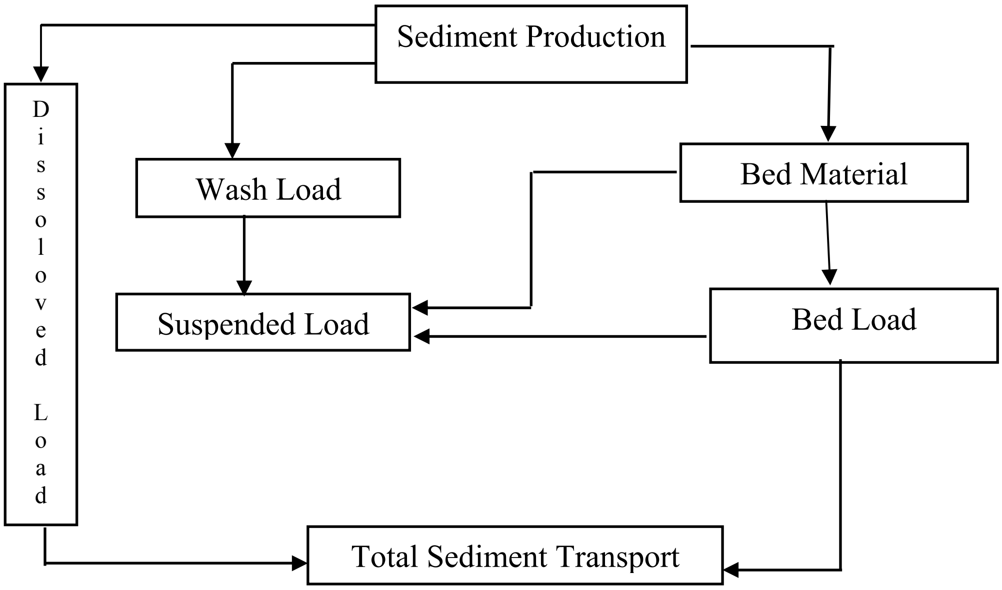

Fig. (15) Schematic for Sediment Process

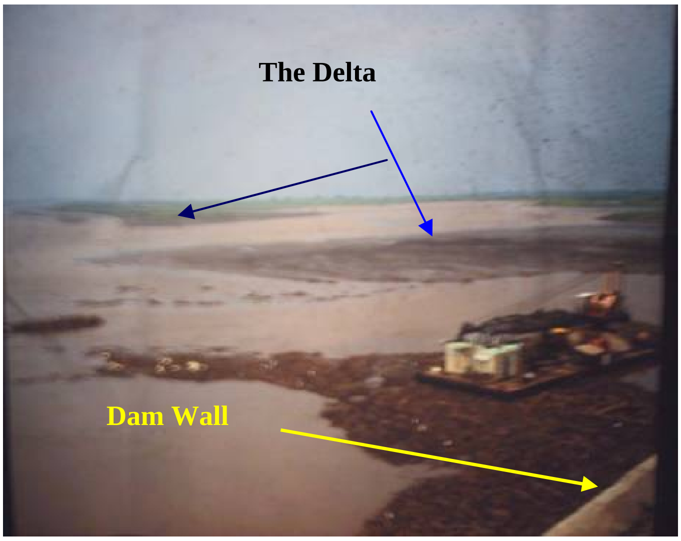

Plate (1) Delta Formation U/S Roseries Dam

3.3 Lake Victoria Watersheds Land Degradation and Erosion

i- Kenya

The main types of soil erosion in Kenya are: sheet, rill and gully erosions which are caused by surface runoff in the wet season. On the other hand, Kenya in the dry season also suffers from wind erosion.

One of the major contributors of sediment, in the Kenyan part of Lake Victoria Basin, is Nyando river. Its basin is made up of six sub-catchments namely: Mbogo, Tugunon, Masaita, Namuting, Ainapsiwa and Nyando, Ndwallah and Nyangaga (2007).

The main type of soil erosion in the Nyando Basin is the gully erosion which is mainly due to heavy water runoff during the rainy season. Consequently it caused some parts of the Nyando river basin to suffer from very severe gully erosion, Plate (2).

Due to high sedimentation on the bed, frequent flooding is happening in the Nyando, Nzoia and Sondu rivers and occasionally in the Yala and Kuja/Migori rivers. This high rate of sedimentation is attributed to the increased destruction of forests in the Mau escarpment hills to give way for settlements and cultivation.

Spatial analysis using aerial photographs and satellite images of the major river basins within Kenya indicated that the Nyando and the Kagera river basins are the high in terms of sediment transport and river discharge, ICRAF (2000), Plate (3).

Removal of top soil is enormous in most areas of Nyando catchment. ICRAF (2000) carried out a study on the rate of surface soil loss, and found out that serious erosion occurred in the catchment (90 t/ha/yr). In the cultivated areas the soil loss rate of erosion is 87 t/ha/yr a bit lower when compared with the previous values. Suspended sediments samples were collected from Nyando river to help in assessing the soil loss. Measurements of soil loss rates in degraded areas were found to be 67 t/ha/yr, which is the highest value of the experimental plots. In grazing area the soil loss rate was only 23 t/ha/yr and on roads and footpaths was 28 t/ha/yr. The latter soil erosion rates are lower compared to the previous ones, which show the difference between the measured and calculated values. Qualitative and quantitative assessment of soil erosion and sediment transportation and accumulation conducted in the basin, revealed that the sediment delivery ratio is about 20.1 %. The study also revealed that, 61 % of the basin is a sediment source area with a net erosion of 43 t/ha /year, while 39 % of the basin is a sink area.

Plate (2) Severe Gully in Nyando River Basin

Plate (3) High Sediment Load Near the Mouth of the Nyando River

ii- Uganda

In Uganda the major contributor of non-point pollution to Lake Victoria basin is Kibale river. This is mainly attributed to the size, topography, human activities, and the nature of the soils. It drains the second largest terrestrial sub-catchment of Bukora river, which is located in the south-western part of Uganda. The discharge varies every year, with an average sediment yield of 5.65 t/km^2/yr.

The dominant type of soil erosion in the Bukora sub-catchment is caused by the water runoff, which causes the sediment processes, the detachment of soil particles and hence the transportation in the river systems (Majaliwa et al (2004), Magunda and Majaliwa (in press), Magunda and Tenywa (2001), Tukahirwa (1995).

Magunda and Majaliwa (2007) used information from different studies to generate the erosion hazard map for the entire Lake Victoria basin in Uganda, Fig. (16). These studies show that soil erosion is wide and varies in type and magnitude from place to another across the farming systems depending on the land use system, population pressure, and the vulnerability of the soil and relief to erosion. However, it was observed that soil loss rates were the highest on bare soils, followed by annuals, degraded rangelands and perennials. Table (2) shows soil loss rate (yield) for various land uses in the Bukora micro-catchment. The major land-use covers are degraded rangeland, perennials, grasslands, forest and woodland. It can be noted that degraded rangelands and perennials contribute the highest erosion rates.

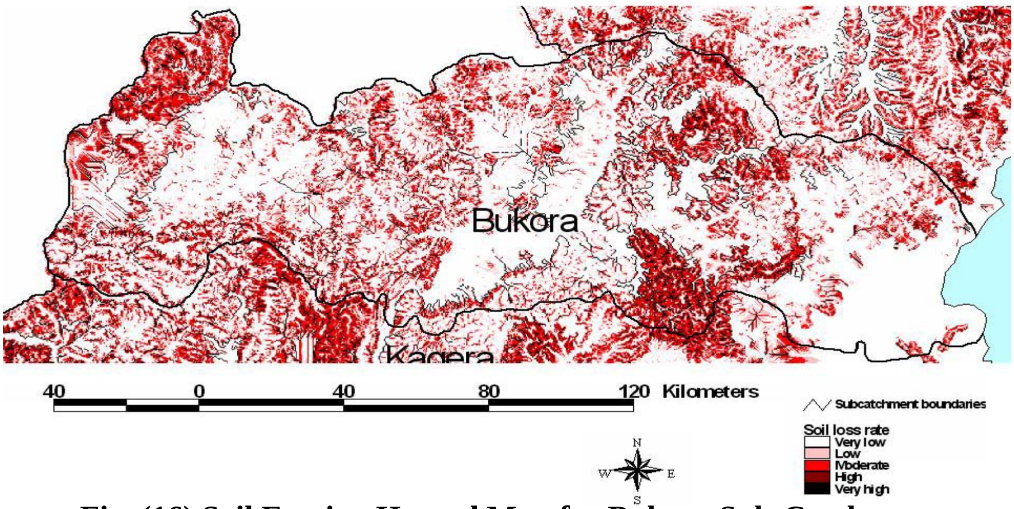

Fig. (16) Soil Erosion Hazard Map for Bukora Sub-Catchment

Table (2) Land-use Contributions, Average Annual Sediment, and Runoff Data

Land-use type	**Area (%)**	**Land use contribution and average export**			
		Sediments			**Runoff**
		Cont	**ER**	**Yield**	**Cont**
		%	t/ha/yr	t/ha/yr	%
Degraded rangelands with patches of annuals	33.0	67.0	69.4	2.5	26.17
Perennials with patches of annuals	37.1	26.7	27.4	0.77	23.34
Grasslands	13.9	4.5	2.0	0.14	25.45
Forest	0.4	0.00	2.0	0.01	0.04
Woodland	15.6	1.8	7.4	0.17	25.0

Cont.: Contribution; ER: Soil loss rate; TP: Total Phosphorous TN: Total Nitrogen
Source: Majaliwa *et al.* (2004)

iii- Burundi

Burundi Nile basin is located in the central plateau and depressions of north Burundi. Many parts of Burundi Nile basin are witnessing soil degradation (erosion). Soil erosion in Burundi occurs mainly as a result of overgrazing and the expansion of agriculture activities into marginal lands. The country has little forested land remaining due to the uncontrolled cutting of forest trees. This in turn has exacerbated the magnitude of soil erosion. Unfortunately, very limited information is available in this respect, especially the rate of soil erosion and the portion that reaches the drainage system as sediment delivery rate.

Table (3) shows the soil erosion rates for various types of land uses or treatments. No data is available on the rate of sediment delivery to drainage system or/and Nile river system.

Table (3) Effect of Terracing on Soil Erosion from Cassava Plantation on Steep Lands in Burundi

Treatment	*Slope (%)*	*Soil erosion (Mg/ha/yr)*	
		1981-82	*1983- 84*
Forest	45-50	0	0
Cassava (terraced)	49	5 2	11.1
Cassava (unterraced)	49	87.4	71.6
Bare plowed	40	441.4	428.2

iv- Tanzania

The main type of soil erosion in Lake Victoria basin, in Tanzania site, is sheet erosion. The annual sedimentation yield received by Msalatu reservoir which was constructed on Simiyu river is 406 m^3/km^2. The reservoir sedimentation corresponds to a soil denudation rate of 0.20-0.73 mm per year.

A study carried out to predict soil loss in relation to land use types within a micro-catchment of the Lake Victoria basin (LVB) showed that the highest soil loss from the cropland was found to be 93 t/ha/yr, followed by rangeland (52 t/ha/yr), and for banana–coffee (47 t/ha/yr), banana (32 t/ha/yr) and forest and papyrus swamp (0 t/ha/yr). In the terrain units, soil loss was highest within the back slopes (48 t/ha/yr) followed by the summits (42 t/ha/yr) and valleys (0 t/ha/yr). For the soil units, soil loss was highest in the Chromic Luvisols (52 t/ha/yr) followed by Petroferric Luvisols (37 t/ha/yr), Mollic Gleysols (5 t/ha/yr) and Dystric Planasols (0 t/ha/yr) in large part, because soil classification often correspond to various slope position.

v- Rwanda

Although there is a limited information on soil erosion and sedimentation in Rwanda, however, some studies reported that the average rate of soil erosion is 34 t/ha. Nyamutera River for example, during only 5 days of the rainy season delivered 567000 tons of suspended sediment to its mouth, or more than half of the basins annual suspended sediment yield. Theoretical distributions of maximum 24 hrs precipitation events suggest that Nyakinama and other regions in Ruhengeri are particularly prone to similar high volume events exacerbating an already serious soil loss problem. Soil conservation is needed to reduce soil loss, augment soil fertility and minimize the impacts of high magnitude and high volume rainfall, is greatly needed.

vi- DR Congo and Eritrea

In these two Nile riparian countries the information of erosion and sedimentation is very limited if not at all available. However, Eritrea and DR Congo have an eager contribution to the Nile system flow, especially in the issue of sedimentation. The current population pressure, inappropriate cultivation practices, forest removal and high grazing intensities on forests, rangelands and marginal agricultural lands, leads to unwanted sediment and stream flow changes that mainly impacts the downstream human and natural communities. In both countries pastoral areas are subjected to growing human and livestock populations, leading to land degradation, soil erosion and increase the load of non-point pollutants.

In DR Congo deforestation is rampart in most natural areas where clearing of forest areas is done for subsistence farming. Therefore, some mitigation measures are needed to be put in place, which can include, (i) reforestation programmes, (ii) land reclamation programme in badly eroded areas, (iii) reviewing, updating and enforcing forestry policy and legislation within the Nile Basin countries, (iv) provision of alternative energy sources to the rural population dependant on firewood.

3.4 Soil Erosion and Land Degradation in Ethiopian Highlands

It is a fact that 85% of the Nile river annual flow for downstream countries (Sudan and Egypt) comes from the Ethiopian Highlands via the Blue Nile, Atbara river and Sobat river, while about 65 % of White Nile annual flow is lost in the Sudd area due to evaporation. On the other hand, several studies concluded that all types of land degradation occur in Ethiopia: soil erosion by water (sheet, rill and gully) and wind. Moreover, stream bank erosion, mass movement, biological, physical and chemical degradation are also taking place in the highlands. The severity of erosion could be noticeable by the formation of too deep, wide and large gullies everywhere (cultivated land or uncultivated one), Plate (4).

Plate (4) Wide and Large Gullies

The Ethiopian Highlands Reclamation Study (EHRS) of 1984 for erosion assessment concluded that 1900 million tones of soil were annually eroded from the Highlands, which is equivalent to an average net of 100 tons/ha soil loss, i.e. 8 mm depth annual soil loss.

Besides natural factors, e.g. torrential rainfall and nature of landscape, there are several causes which accelerated soil erosion in the Ethiopian Highlands and mainly related to the human activities:-

- Population growth,
- Cultivation of steep lands without applying conservation practices.
- Poor farming practices and continuous cropping without nutrient recycling.
- Overgrazing and improper landuse practices,
- Severe deforestation,
- Very low level of soil management.

The soil erosion and land degradation have their negative impact on the socio-economical situation in the Ethiopian population. FAO (1985), indicated that the average annual yield declined from (1 to 3%) on cropland (average 2.2 % for the Ethiopian Highlands) and up to 1% on grassland.

The land degradation could cost Ethiopia over 2.0 billion US$ in 25 years, i.e. 80 million US$ per year. The soil nutrient depletion reduces crop production by 885, 330 t/yr, which is about 14% of the agriculture contribution to Ethiopian GDP. About 80% of the losses would result from reduced crop production and the remaining 20 % coming from reduced livestock production. However, in other studies the estimated annual financial losses are roughly 100 million US$ per year.

Chapter Four

Nile Bank Erosion

4.0 Nile River Sediment

Most of the sediment in the Nile flows from the Ethiopian Highlands through the Blue Nile and Atbara river. Nearly all the sediment (~ 95%) comes from the Blue Nile and Atbara rivers during the flood season (July- Oct.). The White Nile and its tributaries lose most of its sediment load by spilling and deposition over flood plains, lakes and marshlands inside Sudan.

ElMonshid et al (1997) estimated the sediment load of the Blue Nile at El Diem (the entrance of the river to Sudan) to be 140 million tons per year. At the same time their estimation of the sediment load at AHD was 160 million tons taking into consideration the amount of sediment transported by Atbara river. This is compared to 150 Million tons for Mississippi river, 250 Million tons for the Colorado river and 1600 - 2000 Million tons for Yellow river in China. On the other hand, there is no reliable means of bed load information in the Nile river, which is believed to be negligible. However, Hurst et al, (1978) estimated the bed load to be 25% of the total sediment load. The author of this report believes what has been reported by Hurst et al (1978) is exaggerated and far from the reality, the bed load may be less than 20 %. This is confirmed by what was mentioned in Hussein (2006) power point presentation in the ISI Conference where he considered the bed load as 15%. The coarser sand usually deposits in the upper portion of the Blue Nile near the Ethiopia/Sudan boarder, while the lighter sediment is carried by the flow downstream. The suspended sediment load in the Nile system is mainly distributed as 30% clay (< 0.002 mm grain size diameter), 40% silt (0.002 – 0.02 mm) and 30% fine sand (0.02 – 0.2 mm). Therefore, the sediment load in the Nile river can be considered in general as wash load. Fig. (17) compares the average amount of sediment load in different tributaries of the Nile river, while Fig. (18) shows the sediment concentration throughout the year at AHD. It is clear that the peak of the sediment concentration in AHD reservoir falls within the period August-September, although the values are small due the fact that most of the sediment settled in the entrance of the reservoir inside Sudan. In other words it can be concluded that the AHD has 100% trap efficiency.

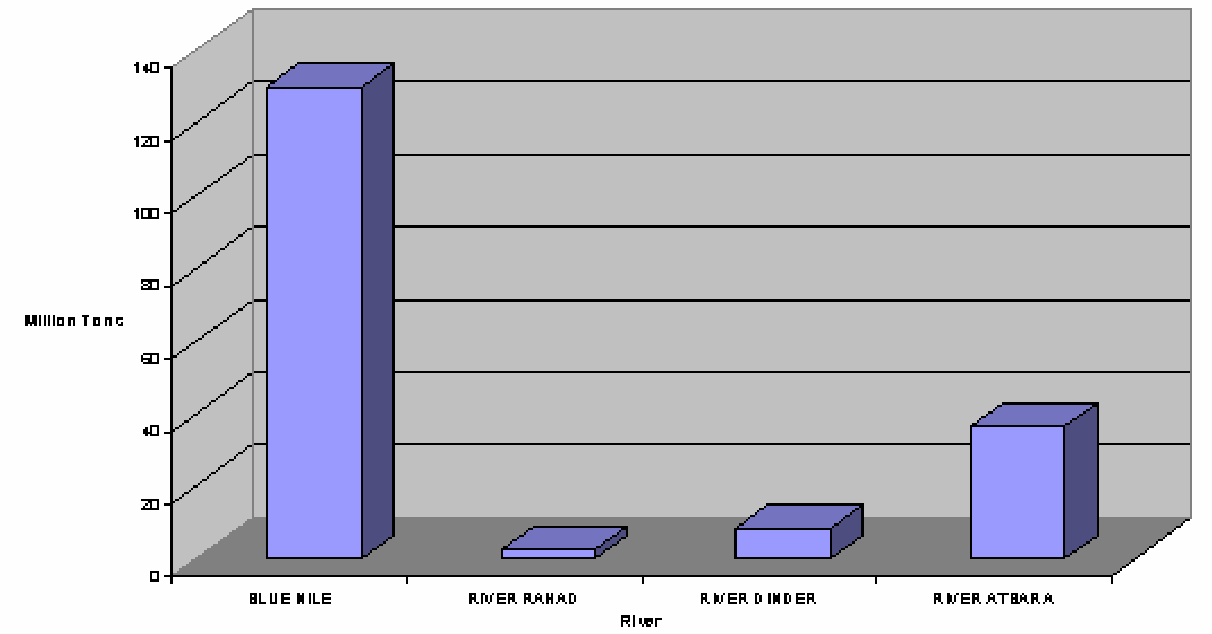

Fig (17) Sediment Load in Different Tributaries of the Nile River

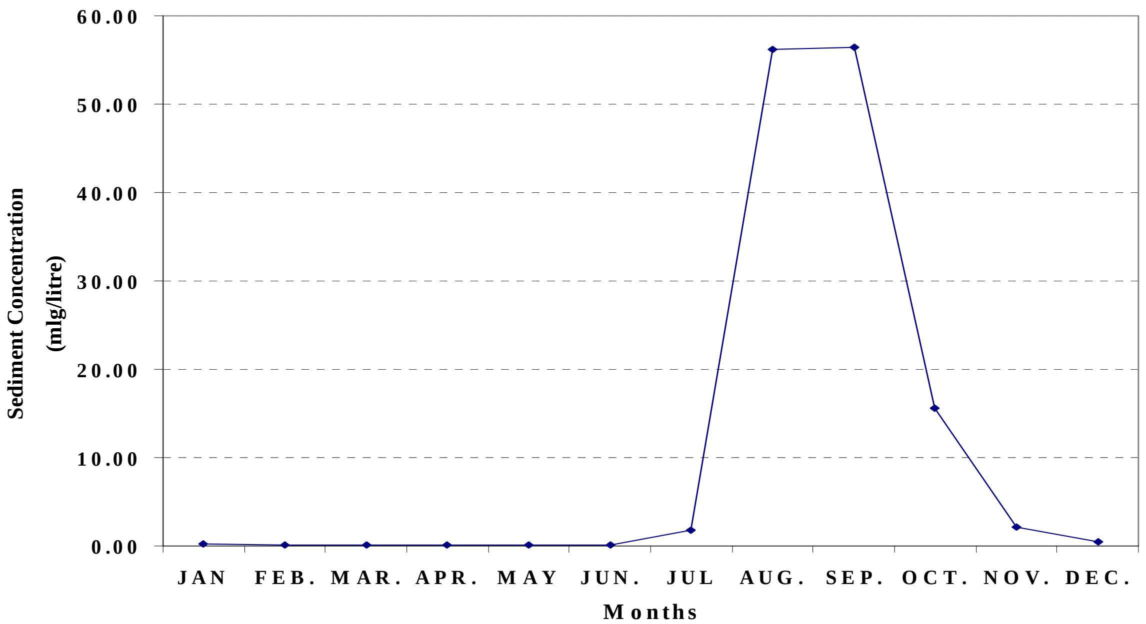

Fig (18) Suspended Sediment Concentration in AHD Reservoir

It is important to clarify and estimate the transport of sediment throughout the entire Nile Basin system in order to implement integrated sediment control and management system. Using different techniques and methods the FRIEND/Nile programme attempted to quantify and qualify the sediment in the Nile Basin for better and sustainable management. However, primary results of the first phase were reported in Sharm Elsheikh Conference, Dec. 2005. Now the project is in its second phase and is expected to end by 2009.

Figs (19, 20) compare the discharge, the total amount of rainfall in the watershed and the sediment concentration for the Blue Nile and Atbara river. The peak of the average discharge is (513 million m^3 per day), comes after the peak of the average sediment concentration (5660 ppm) by about three weeks, while the peak of the total rainfall (2123 million m^3 per day) comes one week before the peak of the discharge. Although there are small discrepancies between the two rivers, however, the sequence of incidents from the technical point of view is quite sound, systematical and logical. These are attributed to the fact that at the beginning of the rainfalls on the top soil in the catchment area which is bare, loose and easy to be carried out by the runoff into the drainage system and hence the river channel. The time lag between these peaks depends totally on the rainfall intensity, duration and the conditions of the catchment area. Sediment starts to increase from the early June until it reaches its peak towards the end of August and beginning of September for both rivers and hence decline towards the end of the rainy season after October. On the other hand, if we consider the water discharges measured at ElDeim station at the border of Sudan with Ethiopia (just after the Blue Nile leaves Ethiopian to Sudan), as runoffs of the Blue Nile catchment (watershed), the total average runoff coefficient is about 20% while the total average runoff coefficient for Atbara river is about 14%. In previous studies the runoff coefficient 25 % was assigned for the Blue Nile and 12 % for Atbara river. Although it is difficult to verify these values, however, the author believes they are a bit low, since the calculations are complex and may encounter many errors. Nevertheless, the Blue Nile runoff coefficient is higher than Atbara River one. This can be attributed to several reasons:

- Atbara River catchment is north of the Blue Nile one; therefore, it is drier with less green cover.

- Higher sediment concentration in Atbara River compared to the Blue Nile indicates the long period of the dry season and heavy rainfall in short period.
- The Blue Nile contributes to the flow of the Nile system with 65% while Atbara river is contributing with only 16%.

These low runoff coefficients are indicating how serious the problem is, and how difficult it is. The deforestation and the degradation of the Ethiopian Highlands have their clear negative impacts on the whole system. In Sudan, where these rivers run, the situation is even worse.

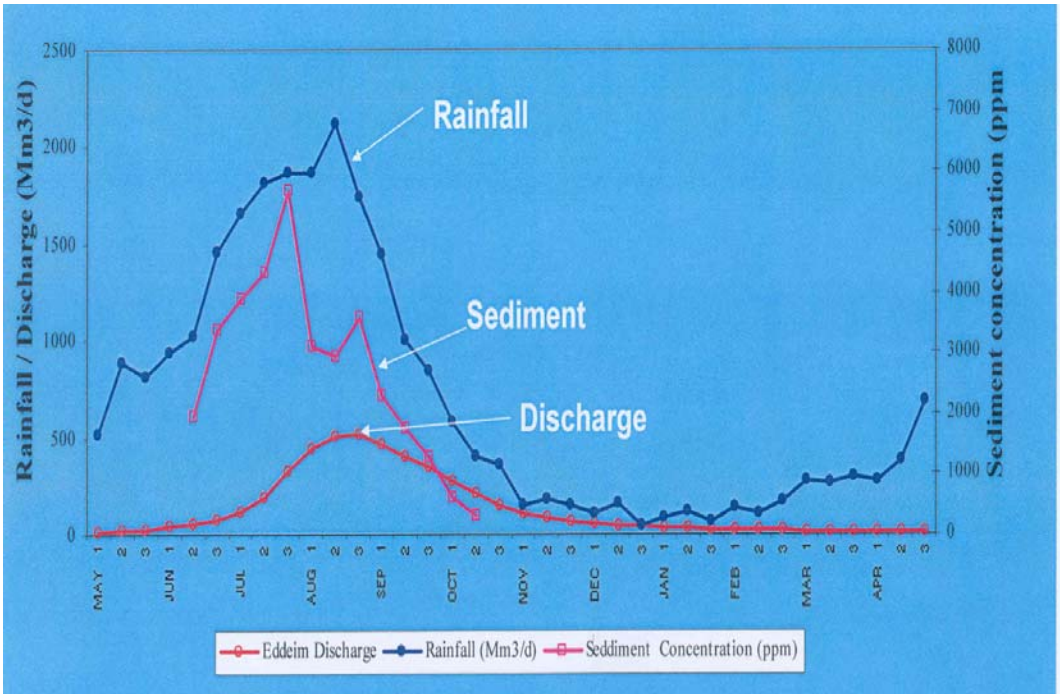

Fig. (19) Comparison of Rainfall, Discharge and Sediment Yield in the Blue Nile

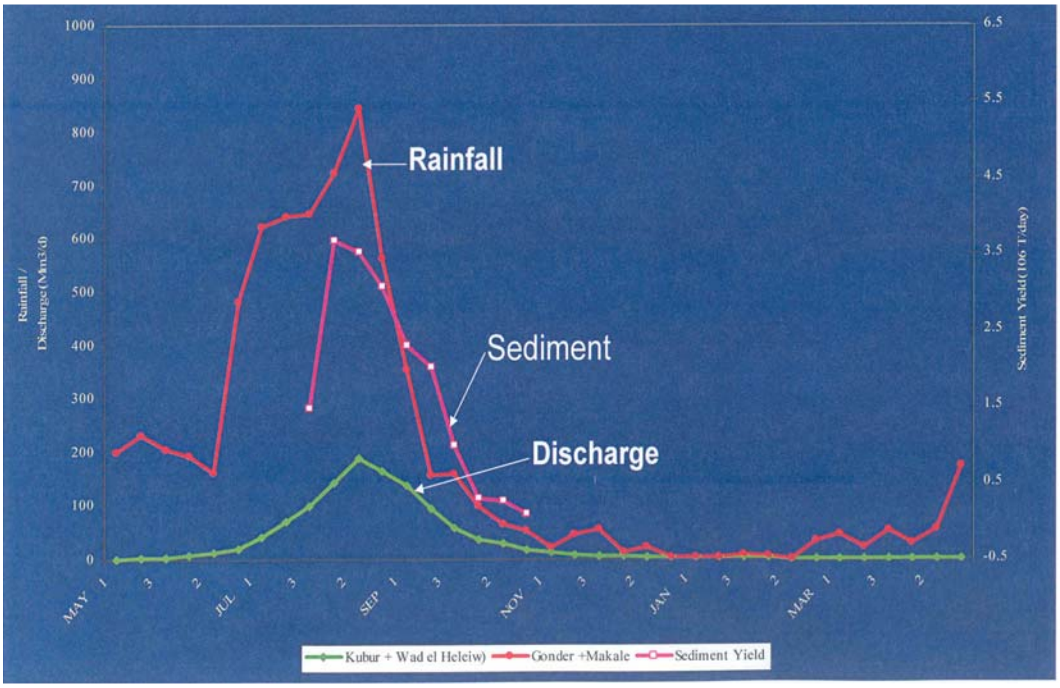

Fig. (20) Comparison of Rainfall, Discharge and Sediment Yield in the Atbara River

4.1 Bank Erosion in the Nile

River bank erosion is one of the most serious problems in river morphology. The process of river bank erosion is a natural process that is unavoidable, therefore the right protection measures must be selected and designed to provide effective, efficient, and durable works after construction. It is a source of sediment in the Nile system especially in the Main Nile, Plates (5, 6). Many factors contribute to the bank erosion; one of them is the interaction between the Nile river water levels during the wet and dry seasons and the groundwater table level. This movement of the water levels up and down causes the bank soils to collapse. Moreover, the high velocity of the Nile water near the outer bends creates serious bank erosion and bank sliding. All these contribute significantly to the sediment in the Nile system. On the other hand, landowners complain of bank erosion and channel shifting, which cause the loss of some parts of their valuable land. For example, the Nuri scheme (3000 feddans) in the Northern Sudan has lost at least 5 % of its land due to bank erosion in the period 1970 – 1980, Osman et al (2004). It is well known that the cultivable land extends only for a few hundred meters along the Nile banks, therefore, it is clear how serious is the problem of bank erosion in such areas. This requires an urgent need for using effective protection measures.

Revetments such as rock riprap, stone pitching, gabions in addition to flow deflectors like spurs dikes are the most widely protection methods used to prevent bank erosion in most of the Nile Basin countries. Rock riprap and stone pitching (revetment) are commonly used in Northern Sudan while in Egypt spurs dikes are used in addition to different types of stone revetment.

Many studies were conducted in the Nile river to investigate the problem of bank erosion. In all these studies the Nile banks were described as consisting of cohesive layers of varying thickness resting on the sandy bed of the river. The colors of these layers vary from brownish to black ones. The top layer is highly cohesive with large amount of clay and silt. It has been observed that at many locations deep and intensive tension cracks develop at the surface of this top layer. These tension cracks contribute significantly to the instability of the banks and hence to the sediment contribution in the Main Nile.

Although the Nile flows are well regulated downstream the AHD but still certain reaches of the Nile river are prone to bank erosion, Osman et al, 2004. These are estimated to be about 12% of the river course. Bank erosion is attributed mainly to erosion by induced flow shear, boat waves, free and seeping drainage water in addition to degradation. However, there is no information regarding the contribution of the bank erosion quantity wise to the total load of the sediment in the Nile system. On the other hand, the experience in the Nile basin shows that whatever the type of protection being used, it was observed that the protection works start to show sign of failures in less than a decade after their construction. Then, in a short time complete collapse occurs. The cause of failure in many cases is attributed to the improper laying of the foundation of the protection while in certain cases it is found that certain design considerations were not included in the design processes. Therefore, certain design considerations and hydraulics relations should be used to calculate the scour depth so as to decide on the proper foundation depth for protection works such as revetments and spurs dikes. Therefore, better understanding of the behavior of the bank erosion is very important in the Nile system for proper bank protection design and environment protection. Moreover, the bank erosion as a source of sediment requires more research to understand the process itself, and hence determine its contribution and impact on the sedimentation mechanism. Furthermore, it is required to know the bank erosion socio-economic and environmental impacts on the whole on the Nile Basin.

Plate (5) Bank Erosion in the Main Nile

Plate (6) Irrigation Canal Buried With Sand Dunes in the Northern State – Sudan

4.2 Sand Encroachment on the Nile River

Natural rivers are exposed to morphological changes due to many factors, which could be internal or external ones. One of the external factors is the sand encroachment. The moving of sands of different sizes (fine and medium) occupies great areas of the banks of the Nile river system particularly in northern Sudan, Plate (7). Table (4) shows the average wind speed in several cities situated on the Nile banks in northern Sudan.

Plate (7) Sand Nile River Bank in the Sudan Northern State

An example is the adverse impacts on the economic and agricultural activities, a matter that was quite felt in the day-to-day lives of the peoples in these areas.
One of the areas in which relative information is available is the Northern State (Sudan), which is confined between latitude 16° and 22° N and longitudes 20° and 32° E. It borders Egypt in the north and extends west to the borders with Libya and Chad.
The northern part of Sudan lacks any vegetation cover except from very few scattered trees and bushes in the wadis. This bare surface has enhanced the wind activities.

Table (4): Average Wind Speed (m/sec) Period (1941-1970)

Station Months	Wadi Halfa	Dongola	Karima
Jan	4.0	4.0	3.6
Feb	4.0	4.0	4.0
Mar	4.5	4.5	4.0
Apr	4.5	4.5	4.0
May	4.5	4.5	4.0
Jun	4.0	4.5	3.6
Jul	4.0	3.6	3.1
Aug	3.6	4.0	3.1
Sept	4.0	4.5	3.1
Oct	4.0	4.9	3.6
Nov	3.6	4.5	3.6
Dec	3.1	4.0	3.6
Yearly	4.0	4.3	3.6

Plate (6) shows irrigation canal buried with sand dunes, while Plate (7 & 8) demonstrate how the sand encroachment choked the Nile river course. If this phenomenon continues in the same manner, the Nile will change its course, a phenomenon already happened in the far past.

Plate (8) Sand Encroachment Choking the Nile River

4.3 Assessment of the Extent, Trends and Impacts of Shifting Sands

Moving sand dunes can overwhelm settlements, fields and roads. The dominant wind direction is from the northeast. Thus, the most hazardous dunes are located to the northeast of the Nile. These are located between Dongola and Korti, Fig. (21). There are 14 smaller dune fields close to the river, and three larger fields 20 to 60 km from the river. The source areas for the dune fields are the very extensive areas of loose and shifting sand that overlies the rock pavement as well as the three larger dune fields to the northwest. These hazards endanger the Nile river course by sand encroaching towards it, whilst the rest is expected to settle in the irrigated fields. The smaller dune covers an area of 14,300 ha.

In the absence of any measurements it is difficult to estimate the amount of sand tipping into the Nile river. On the other hand, one of the main negative impacts of the sand deposition at the bed of the Nile river is the raise in the bed level and hence the flood risks. Several studies attributed the huge and wide damages faced the northern part of the Main Nile during the 1988 and 1998 floods were enhanced by the sand sedimentation on the Nile course bed. The contribution of wind erosion to the Nile river sedimentation is not well known. Therefore, studies in this area are highly recommended.

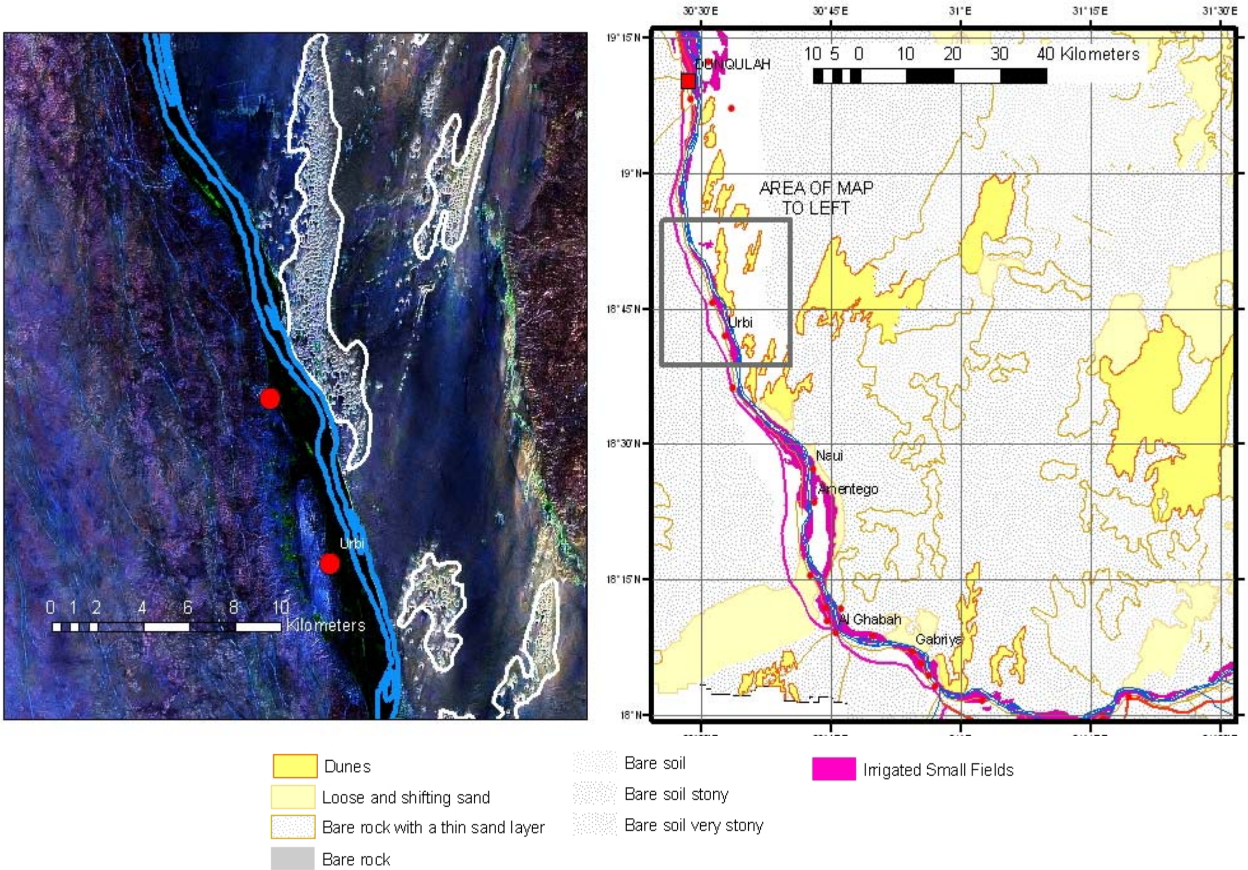

Fig. (21) Dune Fields – Main Nile - Dongola to Korti - Sudan

Chapter Five

Reservoir Sedimentation

5.0 Reservoir Sedimentation

Construction of dams on numerous rivers throughout the world must be the greatest achievements of human beings in river development and greatest disturbance to the stream ecology. However, reservoirs are built for a number of various reasons, either single or multi-purpose reservoir. Most reservoirs are multi-purpose in a combination of two or more of the followings: irrigation, hydropower, water supply, flood control, navigation, fisheries, recreation, and environmental requirements.

The selection criterion here is to make reasonable balance between single- and multi-purpose reservoirs. In the Nile system there are all kinds of dams: single-, twin-, and multi-(more than two) purpose reservoirs. In this report we are going to reflect on the impact of reservoir sedimentation on its purpose(s) and in general the environment.

Large dams cause many problems, especially the sedimentation in the reservoir and erosion in the downstream reaches, besides, disturbance to the stream ecology, e.g. AHD. Furthermore, impoundment of rivers, dam construction, dam failure and dam removal, management strategies of reservoir sedimentation, and impact of dams on ecology are important issues to discuss for better water resources management in the Nile Basin.

Natural river reaches are usually in state of morphological equilibrium where the sediment inflow on average balances the sediment outflow. Sediment deposition occurs as the flow enters the impounded reach of a reservoir due to a decrease in flow velocity and drop in transport capacity of the flow. The impounded reach will accumulate sediment and lose storage capacity until a new balance with respect to sediment inflow and outflow is again achieved.

Reservoirs have traditionally been planned, designed, and operated on the assumption that they have a finite (life), frequently as short as 100 years, which will eventually be terminated by sediment accumulation. However, the sustainability criterion was recently introduced by United Nation (UN) towards the end of the last century to suggest a minimum of 1000 years of operation for new designed reservoir projects. However, for existing reservoirs, sustainable sediment management should seek to balance sediment inflow and outflow across the impounded reach while maximizing long-term benefits. Traditional approaches to sediment management have not considered the sustainable use of reservoirs which resulted in losing reservoirs storage capacity rapidly, possibly as fast as 1 % per year, Mahmood (1987).

A 'large dam' is usually defined by ICOLD as one measuring 15 m, or more from foundation to crest, i.e. taller than a four-storey building, or with reservoir capacity greater than 1.0 million m^3. According to ICOLD the total number of large dams in 2003 is 49,697. Although the number of dams built on the Nile and its tributaries is not large, nevertheless, they play a significant role in the socio-economic development of the Nile Basin riparian countries. Irrigation, hydropower generation, water supply and flood control are the most important functions for dam reservoirs on the Nile system. In the drier parts of the Nile basin particularly in Egypt and Sudan, dam reservoirs are indispensable for irrigation though their contribution in electric power generation has declined over the years because of the expansion of the thermal power generation. However, the present hydropower generation is far below the potential in the Nile river system, especially in the Ethiopian Highlands, Sudd area in Sudan and Upstream and Downstream Lake Victoria.

Nile tributaries originating from the Ethiopian plateau carry large quantities of sediment estimated at about 160 -180 million tons annually. Most of this sediment is clay and silt carried in suspension during the rainy season. Dam reservoirs built on these tributaries are experiencing alarming loss in capacity due to sedimentation. In some reservoirs, the annual rate of capacity loss may approach 1.0 %. Sedimentation has serious implications for reservoirs whose primary functions are irrigation, water supply and hydropower. For the former two functions, loss in capacity implies less stored water and for the latter function implies hydropower generation interruption or curtailment. Khashm ElGirba dam reservoir in Sudan for example lost so far 50% of its original capacity in less than 40 years with corresponding reduction in irrigation area. Roseires dam in Sudan generates a fraction of its hydropower potential during the rainy season because:

(i) Frequent blockage of the turbine intakes by sediment debris, and
(ii) Low head available due to a minimum operation level maintained in the reservoir during the rainy season to reduce reservoir sedimentation.

For Angereb dam reservoir in Ethiopia whose primary function is water supply, the time to abandon the reservoir because of fast sedimentation rates is not far away!
Reservoir sedimentation and the consequent loss of valuable water storage are becoming increasingly important in the Nile Basin. There are evidences of steady rise in soil erosion in some parts of the Nile Basin that endangered reservoir projects and caused doubts about the viability of existing and future schemes. The impoundment of water for potable and irrigation supplies, hydropower, and flood control is a necessary step towards socio-economic development of the Nile Basin countries. Ultimately sedimentation may reduce the benefits and, if it is ignored, remedial measures may become either prohibitively expensive or technically unfeasible.

5.1 Nile Reservoirs Sedimentation

The problem of sedimentation has been reflected downstream in terms of sediment deposition in the reservoirs and the irrigation canalization networks, causing flood risks, crops damage, pumps intakes blockage, low production and hydropower generation difficulties. On the Nile system there are several dam reservoirs: two in Uganda, two in Ethiopia and a third under construction, four in Sudan and a fifth under construction, two in Egypt. However, in the Nile Basin several new dams are planned for different purposes.
Assessments of sediment information in the Nile Basin show that suspended sediment dominates the total sediment in transport and few meaningful of bed load transport have been undertaken for the Nile system. Available data suggests that suspended sediment commonly accounts for approximately 90% of the total sediment load.
Reservoir surveys to determine the volume of deposited sediment and hence the loss in capacity by bathymetric survey and other means seem to be made often for larger than smaller size reservoirs. AHD in Egypt is the most frequently surveyed reservoir followed by Roseires and Sennar reservoirs and less so by Khashm ElGirba reservoir in Sudan. Angereb and Koka reservoirs in Ethiopia and Owen and Bujagali reservoirs in Uganda have not been surveyed so far.
Smaller reservoirs (Angereb, Koka, Sennar and Khashm El Girba) are impacted more adversely by reservoir sedimentation than the larger ones (Roseires and Aswan) because the relative loss in capacity is much faster. However, Owen and Bujagali reservoirs receive almost negligible or limited amount of sediment since they are located each after another few kilometers downstream Victoria Lake, where almost all the sediment loads deposits.
Jebel Aulia reservoir on the White Nile in Sudan was constructed by the Egyptians in 1937 and has a storage capacity of 3.5 billion m^3 but it experienced insignificant amount of sediment deposition due to the nature of the White Nile. Another reason is

the presence of the Sudd region in southern Sudan. The Sudd region acts like a filtering body for all suspended sediment and definitely all the bed load settles there. The amount of sediment load brought by the White Nile is considered in order of 5 % or even less from the total sediment load in the Nile system. This small quantity of sediment is attributed to contribution of the Sobat river, which originates from the Ethiopian plateau. In the coming sections more examples of the Nile Basin reservoirs are going to be sited in more details according to the available information.
Khashm ElGirba reservoir presently irrigates half the area it covered in the past, while the time to abandon Angereb reservoir and look for other water supply source is not far away.
AHD reservoir suffers from more persistent water quality degradation such as thermal stratification and non-oxygenation. However Roseires reservoir is the only one which has a complicated sediment behavior, therefore we are going to give it more attention as an example in this study compared to other reservoirs in the Nile Basin.

5.2 Sedimentation in Roseires Reservoir

Roseires dam was constructed on the Blue Nile about 700 km south Khartoum in 1966 with initial reservoir storage capacity of 3.0 billion m^3 at retention level 480 masl. In the early eighties of the last century it was raised to 3.3 billion m^3 at 481 masl. The dam was supposed to be heightened to 490 masl so as its capacity may reach 7.0 billion m^3. ElDeim gauging station was created purposely for the construction of Roseires dam at Sudan-Ethiopia border. It was established in 1962 during the construction of the dam, some 110 km upstream. The station is situated in a deep rock gorge, which is believed to provide a very stable control, reliable and accurate flows. However, in the last three decades ElDeim station has deteriorated to an extent it is not working properly, Plate (9) shows the present situation of the ElDeim gauging station where one of its towers is tilted by 10 cm and the other by 1 cm and the car cable is totally out of order. Moreover, Plate (9) shows ElDeim water levels steps gauge.
Unlike water discharge measurements, sediment monitoring at ElDeim is infrequent, unsystematic and incomplete. Good consistent sediment measurement data is scarce. The sediment transport in the Blue Nile is a seasonal supply limited phenomenon resulting from rainfall-runoff in the catchment area. The suspended sediment is mostly fine material because weathering of the soils of the watershed during long, dry periods produces large transportable load of fine material.

Plate (9) Recent Photograph of ElDeim Gauging Station, Taken by Prof. Abdalla A. Ahmed (2008)

In Roseires reservoir for a given water flow, suspended sediment transport rate is higher during the rising flood stage (July-August) than the falling flood stage (September-October), Fig. (22). This loop in the sediment transport – water discharge relationship (sediment rating curve) is common for many rivers.
Segments of the sediment rating curve is usually approximated by a power relation of the form

$$Q_s = m\,Q^n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

in which
Q_s = suspended sediment transport (M tons/day), Q = water discharge (m^3/s), m and n coefficient and exponent respectively.
The exponent n for many rivers varies little about a mean value of 2.0 (Garde, Raju 1985). Hussein et al (2005) separated, Fig. (22) into two: one for the rising flood stage, Fig. (23), and the other for the falling flood stage, Fig. (24). Hence, observations indicate that for higher flood discharges, the exponent n in Eq. (1) will diminish and approach a value of unity (n=1), which concludes that the sediment concentration is constant and independent of Q. The value of unity for n appears to be a common minimum value attained by many streams at high flood discharge, USDA (1979). Indeed, the Blue Nile at ElDeim follows this trend during the rising flood stage as it can be seen from Fig. (23). Hussein et al (2005) drew a median line of slope of unity between upper and lower envelope lines, they found that its equation can be given by

$$Q_s = 4.286\text{x}10^{-4}\,Q^{1.0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

For the falling flood stage, the data points in Fig. (24) seem to follow approximately a trend having a slope of 2. as indicated by the upper, median and lower lines drawn in the figure to the same slope (n=2). The median line represents the rating curve for the falling stage with the following equation

$$Q_s = 1.837\text{x}10^{-8}\,Q^{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

From the above analysis, Hussein et al (2005) found that $Qs \sim Q^{1.0}$ for rising flood stage and $Q_s \sim Q^2$ for the falling stage. Thus, one cannot expect a unique relationship between Q_s and Q to be valid for both stages. It is to be noted that for both Eqs (2) and (3), linear least squares fit of the logarithms of the data points was not employed because of the considerable scatter that may give erroneous results.

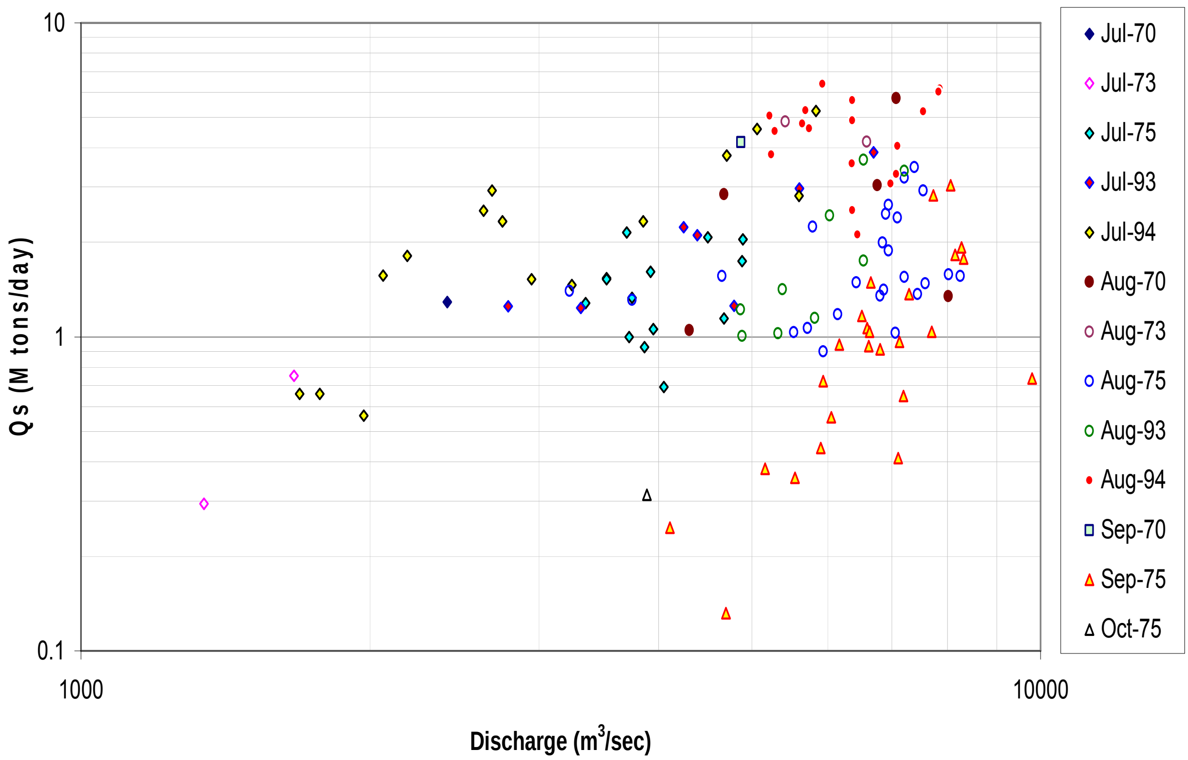

Fig. (22) Suspended Sediment - Water Discharge Relationship for ElDeim Gauging Station at the Mouth of Roseires Reservoir

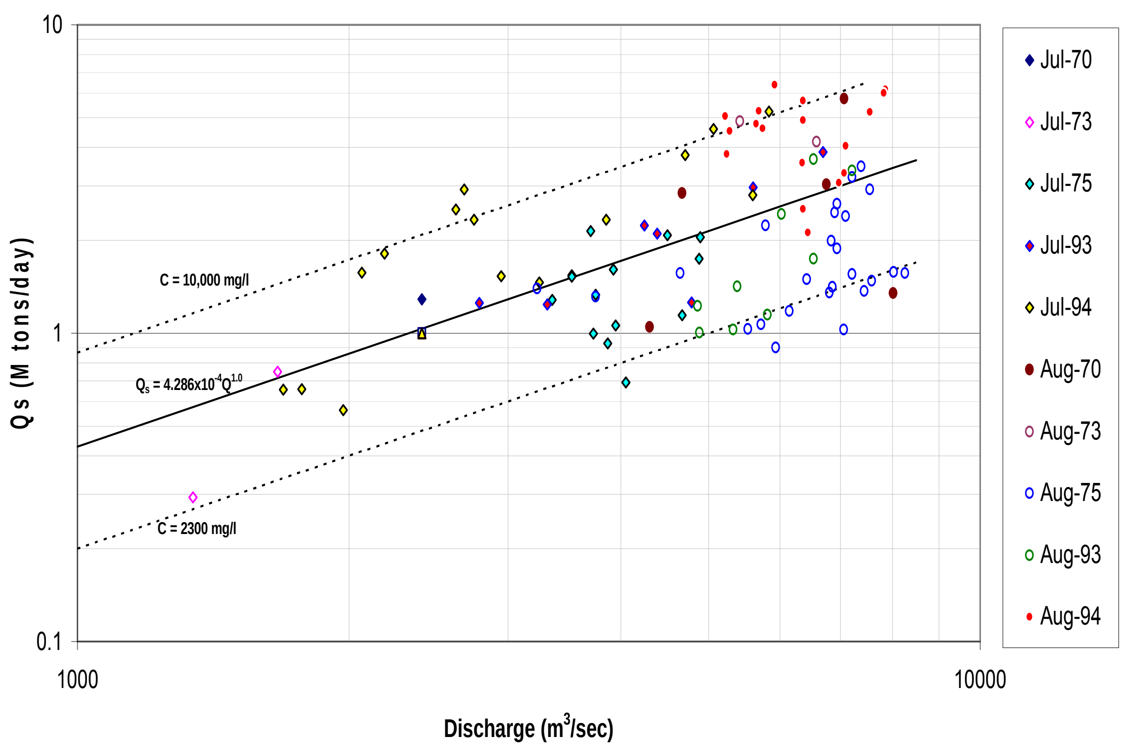

Fig. (23) Suspended Sediment Rating Curve for ElDeim Gauging Station - Rising Flood Stage

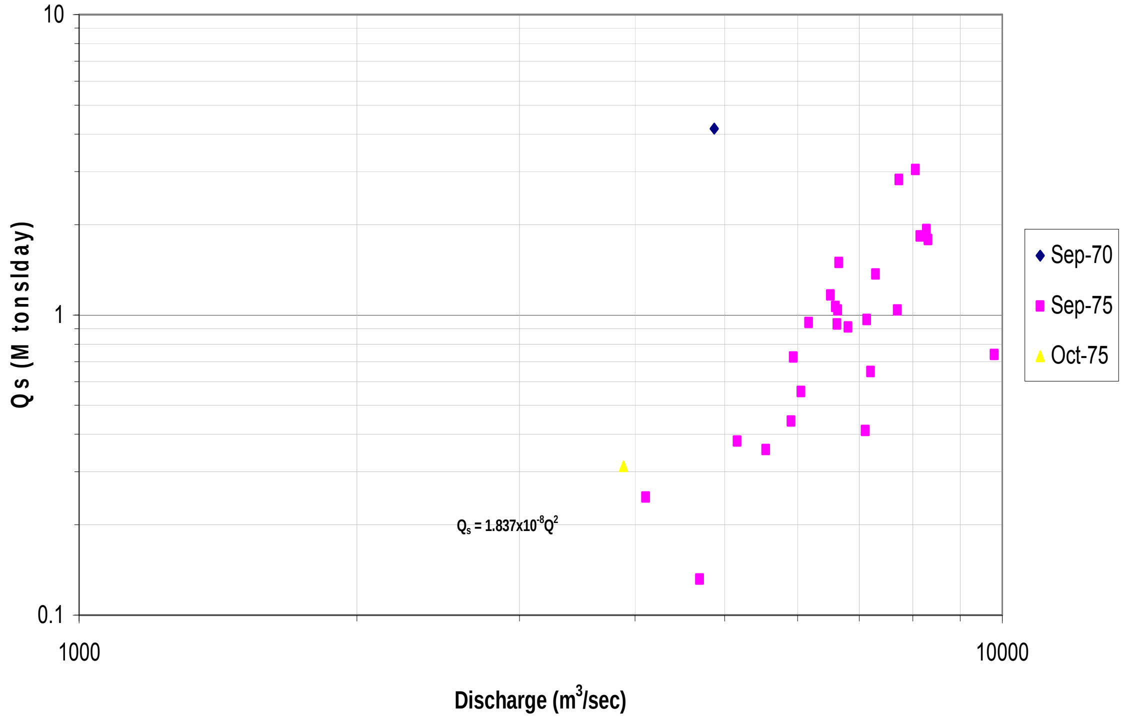

Fig. (24) Suspended Sediment Rating Curve for ElDeim Gauging Station - Falling Flood Stage

5.3 Estimate of Sediment Inflow in Roseires Reservoir

Sediment rating curves are usually based on short-term data record unlike water discharge measurements. However, long-term sediment load estimates are required for reservoir sedimentation. Realizing this difficulty, Miller (1951) developed a method for finding the average sediment yield by combining short-term sediment rating curve with long-term flow-duration curve knows as Flow-Duration, Sediment-Rating Curve method. Experience indicates that the flow-duration/sediment-rating curve method is most reliable when (i) the recording period is long, (ii) sufficient data at high flows are available, and (iii) the sediment-rating curve shows considerable scatter, Julien (1995). Hussein et al (2005) used 30 years flow duration (1966 – 1995) and the sediment rating curves for years (1970, 73, 75, 93, and 1994) at ElDeim gauging station to produce Table (5).

Table (5) Long Term Mean Suspended Sediment Inflow at ElDeim Gauging Station

Month	**July**			**August**			**September**			
Period	**1-10**	**11-20**	**21-31**	**1-10**	**11-20**	**21-31**	**1-10**	**11-20**	**21-31**	
Q_s M tons	**6.55**	**10.40**	**18.76**	**22.29**	**25.98**	**27.31**	**4.97**	**3.57**	**2.50**	
										122.33

Miller (1951) using the above method for the San Juan river in USA. found that the average annual computed sediment transport rate checked within 4% of the average value obtained from a 19-year record.

From Table (5), the value of 122 million tons for long-term suspended sediment inflow at ElDeim gauging station is equivalent to a suspended sediment yield of 480 t/km^2 /yr for the Blue Nile catchment above ElDeim as stated by Hussaein et al (2005). This can be compared with an average suspended sediment yield of 200-400 t/km^2/yr from the 275000 km^2 upper drainage basin of the Blue Nile and Tekezze rivers quoted by Walling (1984) from an earlier published work by McDougall et al. (1975). Walling (1984) presented a tentative and generalized map of the pattern of suspended sediment yields within the African continent. He suggested suspended sediment yield in the range 100-1000 t/km^2 /yr for the Ethiopian Highlands.

Although most of the sediments carried by the Blue Nile occurs during the flood season (July – September) and are predominantly carried in suspension, some sediment is transported as bed load. Also some sediment quantities are transported after the flood season but these are usually insignificant because of the sharp drop in both water discharge and sediment supply. To cater for bed and post flood sediment transport quantities, Hussein et al (2005) added 15% to the seasonal suspended sediment inflow. Therefore, they concluded that the total long-term annual sediment inflow is approximately 140 million tons.

5.4 Trap Efficiency for Roseires Reservoir

Reservoir trap efficiency is defined as the ratio of deposited sediment to total sediment inflow for a given period within the reservoir economic life. Trap efficiency is influenced by many factors but primarily is dependent upon the sediment fall velocity, flow rate through the reservoir and reservoir operation. The detention-storage time in respect to character of sediment appears to be the most significant controlling factor in most reservoirs, Gottschalk (1964).

Trap efficiency estimates are empirically based upon measured sediment deposits in a large number of reservoirs mainly in USA. Brune (1953) and Churchill (1948) methods are the best known ones. Brune presented a set of envelope curves for use with normal ponded reservoirs using the capacity-inflow relationship, while Churchill developed a relationship between the percentage of incoming sediment passing through a reservoir and a reservoir sedimentation index, which is defined as the ratio of the period of retention to the mean velocity through the reservoir.

For a given reservoir experiencing sediment deposition, its trap efficiency decreases progressively with time due to the continued reduction in its capacity. Thus, trap efficiency is related to the reservoir remaining capacity after a given elapsed time (usually considered from the reservoir commissioning date).

The trap efficiency is influenced by reservoir operation procedures. For example there are four main operation periods for Roseires dam reservoir. During the rising flood, the reservoir is drawdown to 467 masl, which is the lowest operating level. Over this operation period, minimum sediment deposition is expected despite the large quantities of sediment inflow, which may reach more than 3.0 million t/d. This is particularly true after many years of continuous operation of the reservoir where a well defined channel, capable of transporting almost the whole sediment inflow past the reservoir during the drawdown period, was developed naturally, Gibb et al (1987).

The reservoir filling period commences after the flood peak has passed. According to Roseires Reservoir Operation Rules, filling may start any time between the 1st and the 26th of September each year depending on the magnitude of the flow at ElDeim. It is seldom and very rare filling starts before or after this period. From past experience, filling normally starts within the first ten days of September when the suspended sediment concentration is still relatively high at about 2500 mg/l. The filling period usually lasts for nearly two months. Due to the gradually rising water level and the relatively high suspended sediment inflow, significant sediment deposition is expected during the filling operation period. In contrast, during the third and fourth operation stages (maintaining full retention level and reservoir emptying), sediment deposition is insignificant due to the exceedingly small sediment inflow quantities. Over the filling period, the water level in the reservoir is raised steadily from 467 masl to 481 masl. Hussein et al (2005) considered the annual inflow of $50x10^9$ m^3 at the 474 masl to estimate the trap efficiency by the following equation.

$$T.E\,(\%) = \frac{(V_o - V)\gamma}{Tx140x10^6} \times 100 \quad \textbf{(4)}$$

Where
T.E. = trap efficiency after T years of operation, V_o = original reservoir volume in m^3, V = volume remaining after T years of operation in m^3, γ = average specific weight of deposited sediment over T years (t/m^3), γ is calculated from the following equation (Miller, 1953)

$$\gamma = \gamma_i + 0.434K[\frac{T}{T-1}(\ln T) - 1] \quad \textbf{(5)}$$

Where γi is the initial value of γ and is given by

$$\gamma_i = \gamma_{cl}\ P_{cl} + \gamma_{sl}\ P_{sl} + \gamma_{sa}\ P_{sa} \quad \textbf{(6)}$$

Where P_{cl}, P_{sl} and P_{sa} are fractions of clay, silt and sand respectively of the incoming sediment. γ_{cl}, γ_{sl} and γ_{sa} are coefficients of clay, silt and sand respectively which can be obtained from the following tabulation (USBR, 1982), and in the case for Roseires reservoir the following values were obtained by Hussein et al (2005).

Coefficients for Clay, Silt and Sand (kg/m^3)

Clay	Silt	Sand
561	1140	1550

The Compaction Coefficient K Values for Reservoir Operation

Clay	Silt	Sand
135	29	0

Therefore, Assumed Composition of Deposited Sediment in Roseires Reservoir

Clay	Silt	Sand
25%	45%	30%

For these assumed values, $\gamma_i = 1.118\ t/m^3$ and $K = 0.0468\ t/m^3$.
Comprehensive field measurement sampling programme of deposited sediment in a number of major and minor canals in the Gezira Scheme was made in 1989 (HRS, 1990). The mean value of γ_i for a depth below bed level (from 80 mm to 500 mm) was 1.061 t/m^3, which is very close to the adopted value for Roseires reservoir considering that the Gezira scheme draws its water from the Blue Nile. The observed and computed trap efficiency values are given in Table (6).

Table (6) Roseires Reservoir Trap Efficiency (%) (after Hussein et al, 2005)

Year of re-survey T (years)	1976 10	1981 15	1985 19	1992 26	1995 29
Observed	45.5	36.0	33.2	28.0	26.2
Brune's Method (lower envelop)	51.0	49.0	46.0	45.0	45.0
Churchill's method	67.7	66.0	64.4	63.5	62.8

It is generally believed that the volume of deposited sediment from the year 1992 resurvey as given in Table (7) was over estimated. Making use of the results of the later resurvey in 1995, it is expected that the trap efficiency in 1992 to be close but higher than its observed value in 1995 due to the relatively short time in between the two resurveys. A value between 1985 and 1995 values may be considered as well. Therefore, a trap efficiency equals to 28% seems reasonable. Accordingly the cumulative volume of deposited sediment V_d between 1966 and 1992 i.e. 26 years of operation is computed from the following formula;

$$V_d = (T.E. /100) \times (140\times10^6 \times T)/\gamma \quad \ldots\ldots\ldots\ldots \quad \mathbf{(7)}$$

Therefore, $V_d \approx 907$ Mm^3, which is the new revised volume of sediment deposition in 1992.

From Table (6), both Brune's and Churchill's methods overestimated the observed trap efficiency values. The deposition rates, however, decreased progressively with time as witnessed from the gradual drop in observed trap efficiency from 45.5% in 1976 to 26.2% in 1995. This trend was not reflected in the computed trap efficiency values using both Brune's and Churchill's methods which remained fairly constant over the years of observations.

Siyam (2000) has shown that Brune's curve is a special case of a more general trap efficiency function given by the following equation:

$$T.E\ (\%) = 100 \exp(-\beta\ V/I) \quad \ldots\ldots\ldots\ldots \quad \mathbf{(8)}$$

Where, in addition to the already defined terms, β is a sedimentation parameter that reflects the reduction in the reservoir storage capacity due to the sedimentation process. Siyam (2000) demonstrated that Eq. (8) with values of $\beta = 0.0055$, 0.0079 and 0.015 describes well the upper, median and lower Brune's curves respectively as depicted in Fig. (25).

Table (7) Roseires Reservoir Volume Characteristics (1966-1995)

Reservoir Elevation (m)	Original Volume Curve (Mm^3)	Bathymetric Survey March 1976		Bathymetric Survey February 1981		Bathymetric Survey October 1985		Bathymetric Survey December 1992		Satellite Imagery Jan. to April 1995	
		Revised Volume Curve Bathy. (Mm^3)	Sediment Deposit Volume (Mm^3)	Revised Volume Curve Bathy. (Mm^3)	Sediment Deposit Volume (Mm^3)	Revised Volume Curve Bathy. (Mm^3)	Sediment Deposit Volume (Mm^3)	Revised Volume Curve Bathy. (Mm^3)	Sediment Deposit Volume (Mm^3)	Revised Volume Curve Bathy. (Mm^3)	Sediment Deposit Volume (Mm^3)
467 (MOL)	636	152	484	91	545	80	556	65	571	39	597
469	861									144	717
470	990	444	546	350	640	282	708	260	730	233	757
471	1131									353	778
475	1820	1271	549	1156	664			1050	770	980	840
480	3021	2470	551	2370	651	2224	797	2093	928	2122	900
481 (FSL)	3326	2775	551	2675	651	2530	796	2332	994	2415	911
			Total 551		Total 651		Total 796		Total 994		Total 911

Source: Gibb, Coyne Et Bellier, July 1996

The relationship between observed trap efficiency and years of operation is shown in Fig. (26). The trend of the data points shows that T.E α $T^{-0.5}$.

This relationship may be used to estimate subsequent trap efficiency of Roseires reservoir. From Fig. (26), the projected trap efficiency after 100 years of continuous operation will be about 14% if conditions remain the same in the mean time. However, when Roseires dam is heightened as planned, this relationship is going to change.

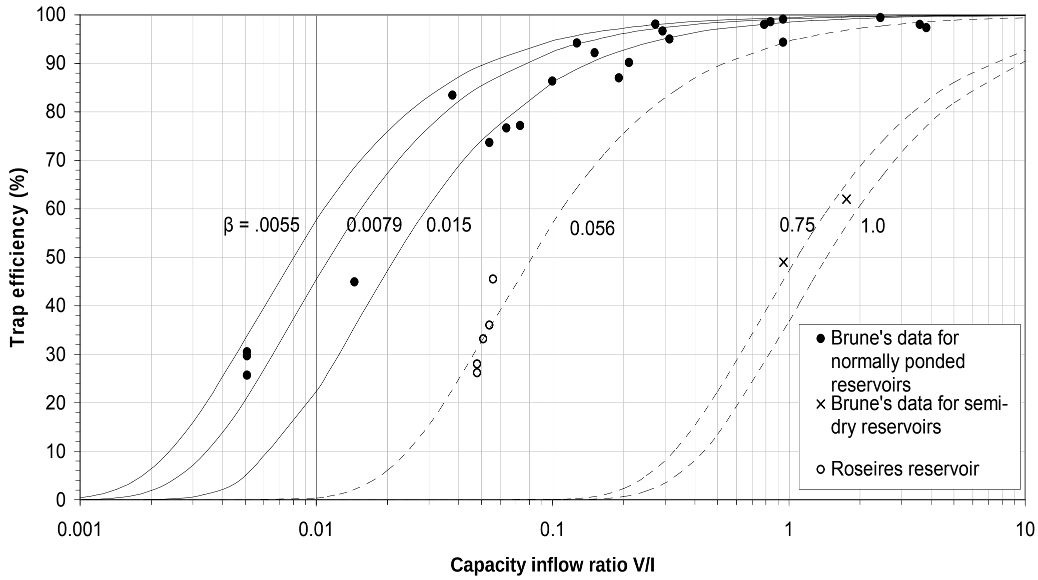

Fig. (25) Comparison of Roseires Reservoir Trap Efficiency Data with that of Brune's

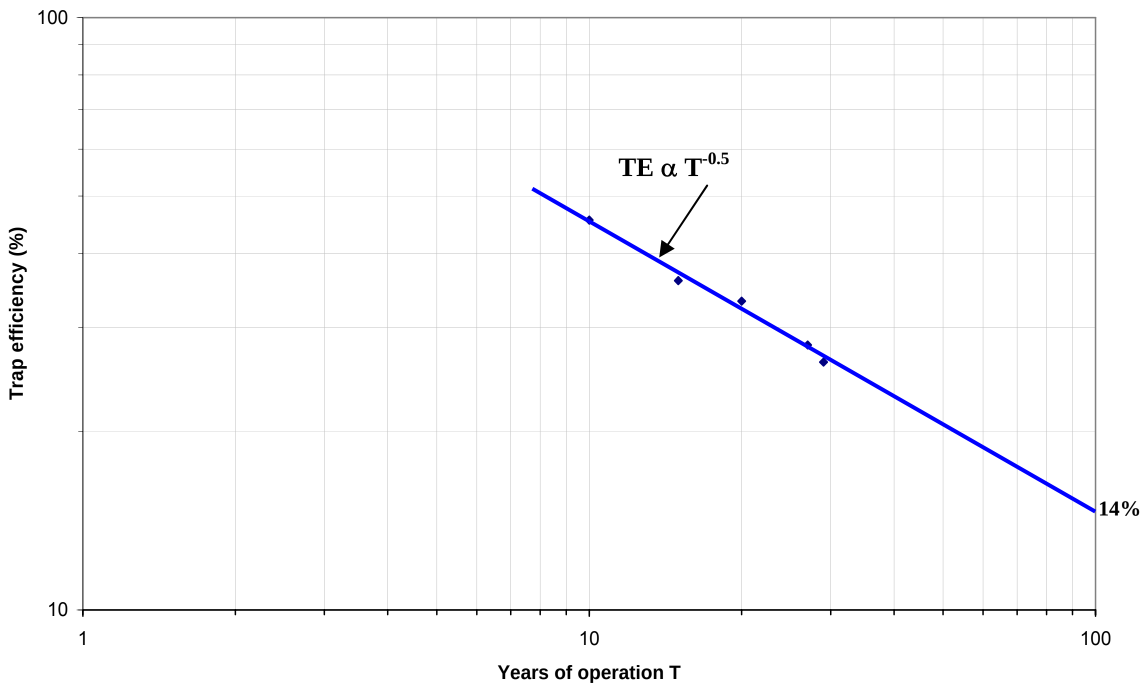

Fig. (26) Relationship between Observed Trap Efficiency and Years of Operation for Roseires Reservoir

5.5 Koka Reservoir

Koka dam is constructed on Awash river, which originates from the Ethiopian Highlands some 150 km west of Addis Ababa, at an altitude of about 3000 masl. However, Addis Ababa represents the water divide line between the Blue Nile watershed and Awash watershed. The Blue Nile run westwards and Awash river run eastwards from the same region, i.e. both of them are originating from the same region.

Koka reservoir had an original storage capacity of 1650 million m^3 at full reservoir level of 1590.7 masl. Fig. (27) shows the corresponding elevation capacity curve for Koka reservoir. When the dam was made operational in 1960 the storage capacity of the reservoir at 1581.1 masl (minimum operating level) was 180 million m^3. At present only 8.0 million m^3 of dead storage volume remains. This means that 96% of the dead storage volume is filled by sediment. Hence this condition has impacted the operational level of the reservoir and has directly affected the uses of the reservoir. Koka dam incorporates a spillway comprising five sector gates, a bottom outlet with maintenance gate and two fixed wheel bulkhead gates.

Several surveys were made in 1959, 1981, 1988 and 1999 to monitor sedimentation in Koka reservoir, see Fig. (27). The mean rate of silt deposition in the reservoir is estimated at 13–20 million m^3 per year (MoWR,1999), which is in the order of 1800 $ton/km^2/yr$. Using the original capacity of the reservoir and the mean annual inflow of Awash river upstream of Koka dam (29478 million m^3 at Hombole station) the trap efficiency is estimated to be 78 %. However, the rate of silt deposition is expected to vary (from year to year) due to land-cover changes in the catchment area and the variation in sediment trap efficiency due to storage changes is obvious. Koka reservoir should be a learned lesson considered for any future dam reservoir on the Blue Nile (Abbay) inside Ethiopia.

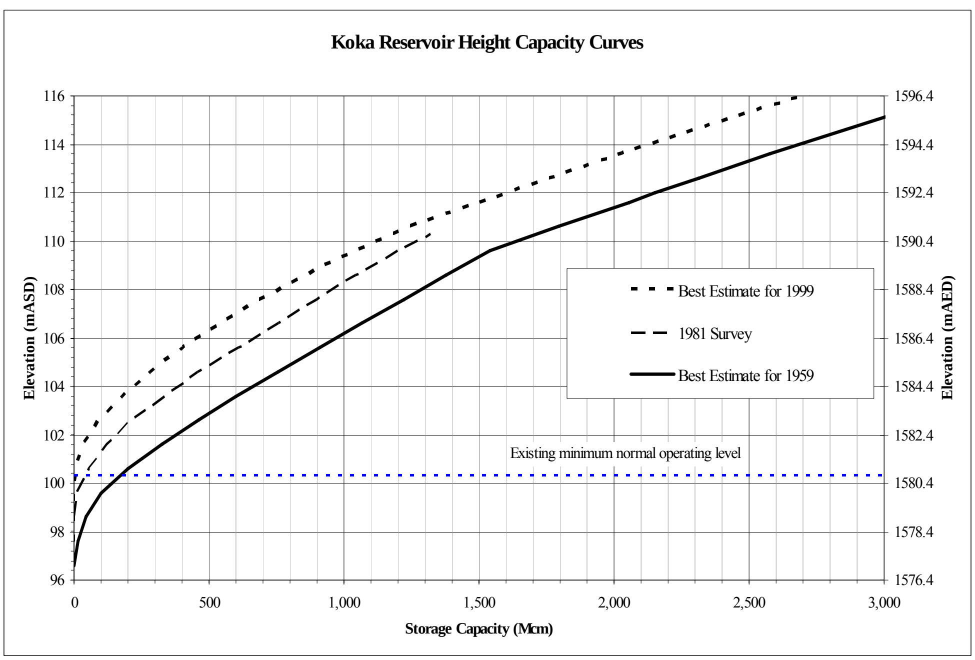

Fig. (27) Koka Reservoir Storage Capacity Curve

5.6 Angereb Reservoir

Angereb dam is constructed for water supply in 1986 on Angereb river, a tributary of the Blue Nile in the Ethiopian Highlands. Angereb watershed is characterized by hilly topographic conditions, absence of vegetation cover, improper farming and soil management practices. Therefore, Angereb river catchment experiences severe soil erosion which contributes to reservoir sedimentation and affects its water supply potential.

The mean annual flow of Angereb river at the gauging station is about 27 million m^3, Fig.(28). The trap efficiency of the reservoir estimated from the original capacity (5.0 million m^3) according to Brune median curve is 90 %. Suspended sediment measurements at the Angereb gauging site show high variability. The mean annual suspended sediment discharge at the dam site in the period of 1983 -1989 was estimated at 76,800 tons, with annual rate ranging from 7,900 to 178,800 tons. Heavily sediment concentrations (25,000 ppm) come with the highest flood peaks in June-October, while in dry season it is less than 300 ppm.

The estimated mean annual sedimentation rate in Angereb reservoir is 1200 t/ km^2/year. Several studies have shown that the reservoir half life would be alarmingly about 21 years. According to their prediction the reservoir lost 15% of its volume in 2005 and would lose about 30% in the year 2015. The water resources verification study carried out by MoWR revealed that by the end of 2010 there will be shortage of water in Gonder town because the reservoir capacity will become less than 50% (from $5Mm^3$ to $2.5Mm^3$) as a result of sedimentation. This is definitely will have its negative impact on the people livelihood. It can be noticed that the estimation of sediment deposition quantified by latter is almost triple that suggested by former in spite there is one year between the two studies. This means that the sediment information is limited and requires more efforts to rectify it. However it seems that the latter is more realistic recognizing the large amount of sediment load originating from the catchment.

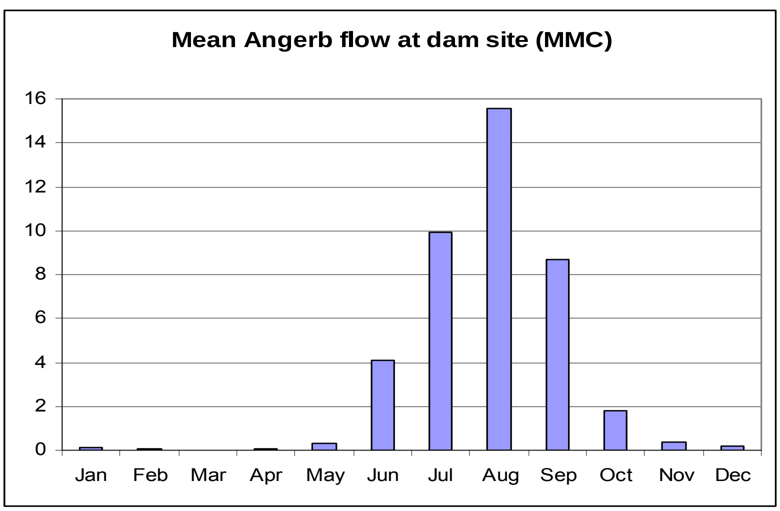

Fig. (28) Angereb Flow at Dam Site

5.7 Sennar Reservoir

Sennar dam is the first reservoir to be constructed on the Blue Nile in Sudan (1925) some 300 km south Khartoum, with a storage capacity of 0.93 billion m^3. The main purpose of the dam is to irrigate the Gezira Scheme and secure drinking water supply during the dry season. Ahmed (2003) reported that the rate of sedimentation of Sennar reservoir in the period (1925 – 1981) had never exceeded ½ % per year (4.6 million m^3) with respect to the original capacity. Therefore, only 28 % reduction in the reservoir capacity in that very long period of (56 years) occurred. In this period the river is left to flow naturally without any impoundment in the reservoir during the flood period (July – Sept.). The other reason behind this perfect performance is the excellent design of the dam where there are 80 deep sluices and 112 spillways gates (currently 2 spillway gates are operational) spreading across the river width, which enable the reservoir to get rid of the sediment during the flood period if that performance was continued in the same manner, the reservoir live time can go up to 200 years. On the contrary, the followed period (1981-1986) sedimentation increased drastically with a rate of 80 million m^3 per year (9½ %) i.e. a reduction of 400 million m^3 (43%) in only 5 years. However, Sennar dam in 61 years lost 71% of its original reservoir capacity (660 million m^3), Fig. (29). In addition to the increase of sediment load in general in the last two decades, however, the main reason behind the heavy sedimentation in the above period (1981-1986) is the change of the operational rules to satisfy the irrigation requirements, for the agricultural schemes, upstream and downstream the dam. Now Sennar reservoir is no longer used to store a considerable amount of water, but to regulate the river flow and to generate hydropower from a limited capacity station (15 Mw). In the first period (1925-1981) Sennar dam represents a best example for the positive impact on sedimentation reduction in a reservoir using proper operation management. This proves that the operation rules are the best effective tool in saving the reservoir storage capacity and for its sustainability. However, after 82 years of operation, it is believed that Sennar reservoir is no longer has a considerable storage capacity.

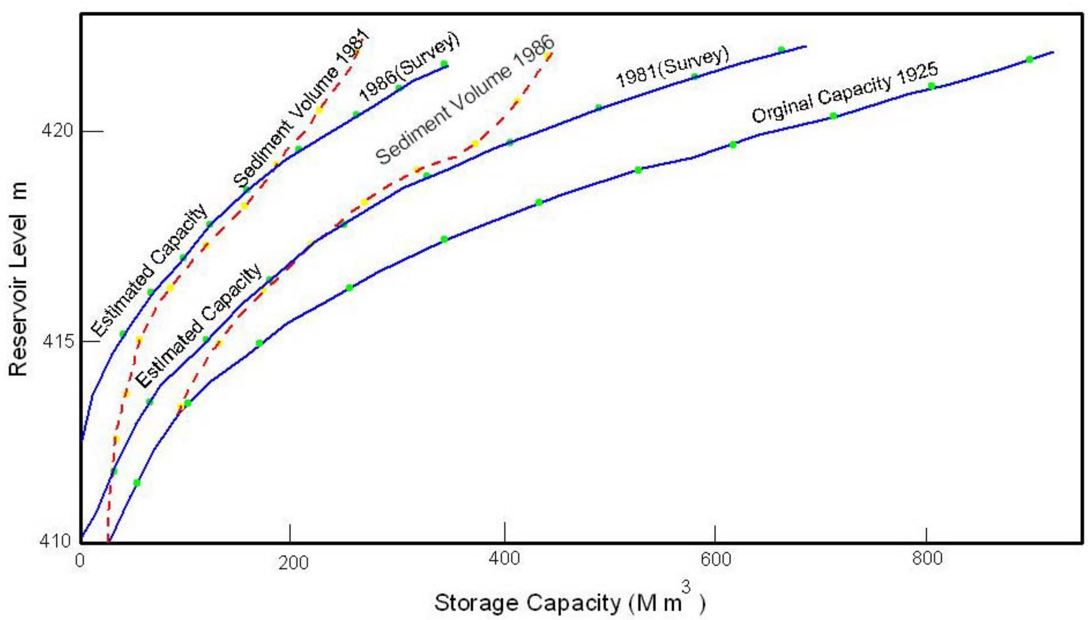

Fig. (29) Sennar Reservoir Storage Capacity

5.8 Khashm ElGirba Reservoir

Khashm ElGirba reservoir is constructed on the Atbara river approximately 200km downstream of the Ethiopian border and 75 km downstream the confluence of the Upper Atbara and Setit rivers. Annually an average sediment concentration of 15000 ppm is carried by Atbara river. Sediment concentration can reach a maximum sediment concentration of 30000 ppm. The mean annual inflow of Atbara river is known to be 2.0 billion m^3 which is the sum of Kubur and Wad El Hiliew (Setit river) gauging stations measurements, however, from Fig. (30) the average main flow is 13.0 billion m^3 for the period (1980-2000). Based on the latter figure and the original reservoir capacity, the trap efficiency of the Khashm ElGirba reservoir reaches 86 %. The dam was initially filled in 1964 with a capacity of 1.30 billion m^3 at the elevation 473 masl i.e. its storage is only 10% of the inflow. The reservoir length is 80 km. in 1977, the storage capacity of the reservoir was reduced by 0.66 billion m^3 due to the sedimentation, which represents 50 % of its capacity. Besides, the natural phenomenon of the heavy sediment load, Atbara river is characterized by steep slopes, ranging from 5 m/km along the 300 km from the starting point in the Ethiopian Highlands to the catchment outlet, and 25 cm/km for the 500 km from Setit river confluence up to Atbara city, where the river meets the Main Nile. This problem is further aggravated by the inappropriate operation policies of the reservoir. The loss of storage capacity caused severe water shortages during drought years resulting in decline of the crop area cultivated. The decline in storage capacity has also caused hydropower generation to be limited to the flood season only. On the other hand, , the drinking water plant for ElGadarif City at ElShowak headworks, which is located in the delta area of the reservoir is endangered of being drowned. This is due to gradual rising of the delta formed at the head of the reservoir by 12 m above the initial bed elevation.

The sedimentation and debris problem at the turbine intakes are causing serious problems. Fig. (31) & Fig. (32) shows Khashm ElGirba reservoir content and hydrographic surveys of the annual rate of loss of the reservoir storage at different levels. Obviously, the existing sediment monitoring program is not sufficient to determine the amount of sediment entering the reservoir. Not only this but even there are difficulties in obtaining reliable water discharge measurements.

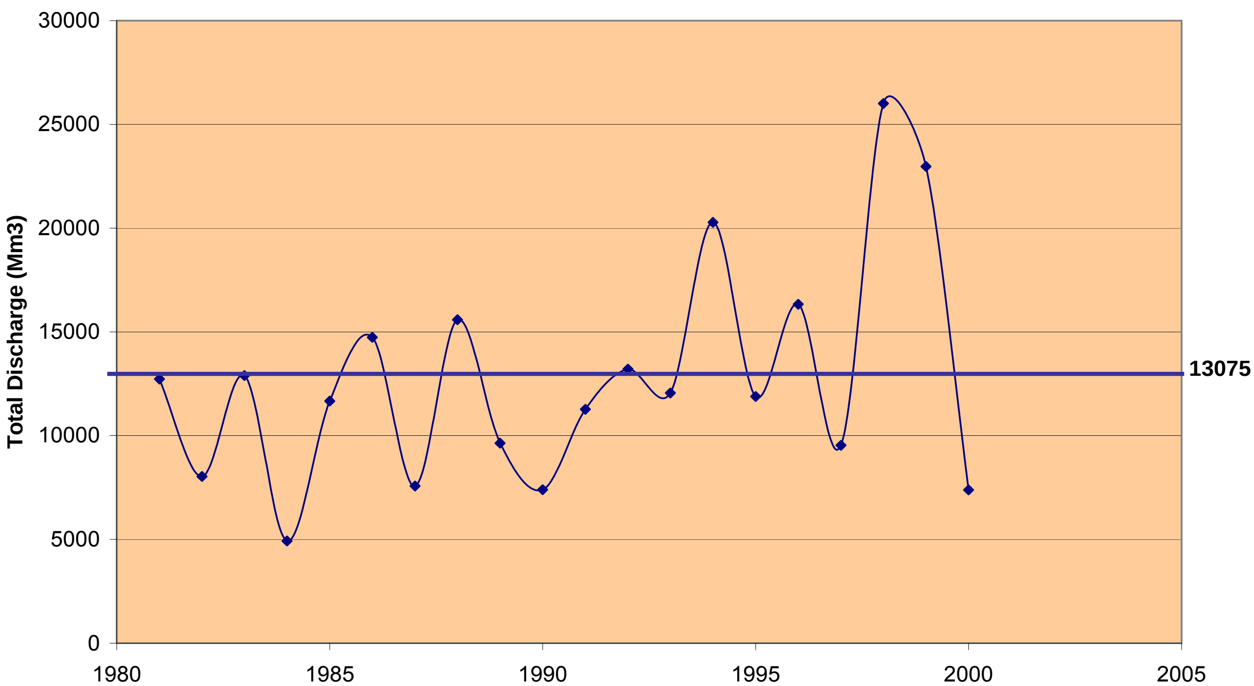

Fig. (30) The Mean Annual Inflow of Atbara River

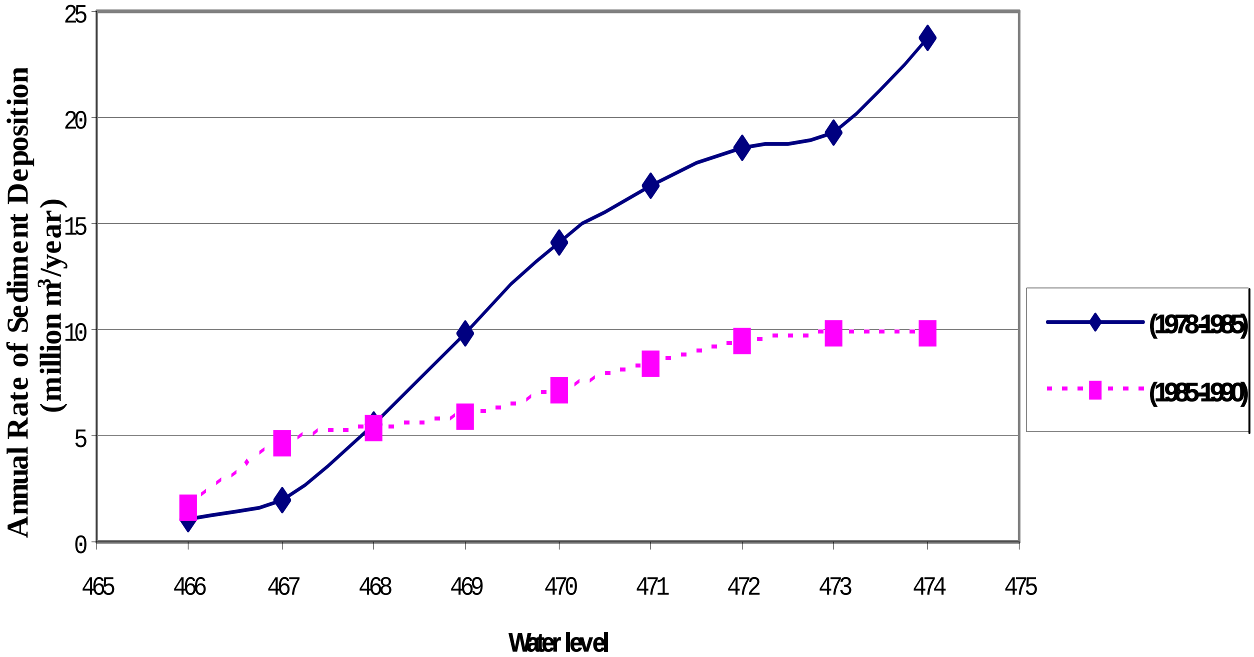

Fig. (31) Khashm ElGirba Reservoir Content

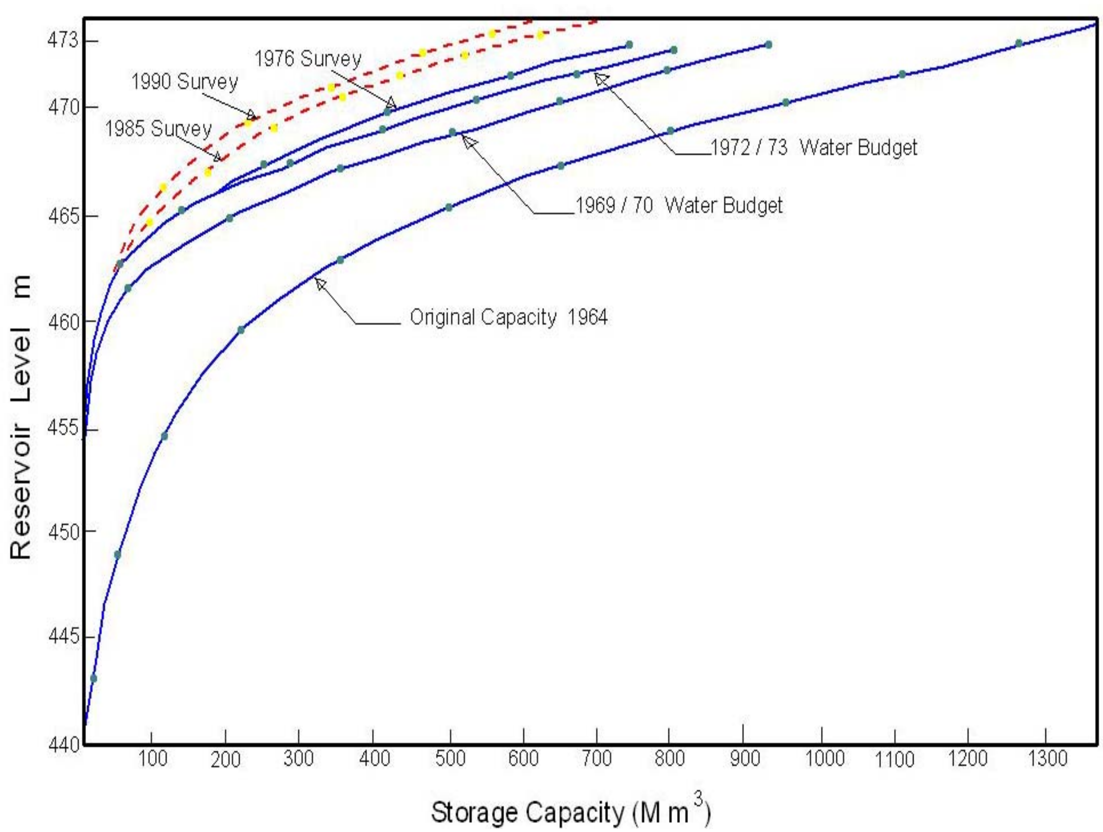

Fig (32) Khashm ElGirba Reservoir Storage Loss Rate at Different Levels

5.9 Aswan High Dam (AHD)

In 1902, Egypt constructed the Old Aswan Dam on the Main Nile with a storage capacity of one billion m^3. Several heightenings were implemented to increase the storage capacity to 5.0 billion m^3 toward the sixties of the last century. Based on the 1959 Nile Waters Agreement between Sudan and Egypt, AHD was constructed to completely control the Nile waters for the benefit of the two countries. The AHD is a rock fill dam, completed in 1968 and fully operated in 1972. It is located 7.0 km south of Aswan City. AHD reservoir extends for 500 km along the Nile River and covers an area of 6,000 km^2, of which two-thirds (known as Lake Nasser, 350 km) is in Egypt and one-third (called Lake Nubia, 150 km) is in Sudan, Fig (33).

The mean annual discharge before and after the construction of AHD are presented in Fig. (34), while Fig. (35) shows the storage level of AHD and the corresponding reservoir content over 25 years. The long-term annual average (1929-1959) of sediment load that enters the Old Aswan reservoir at Wadi Halfa was estimated to be134 million tons.

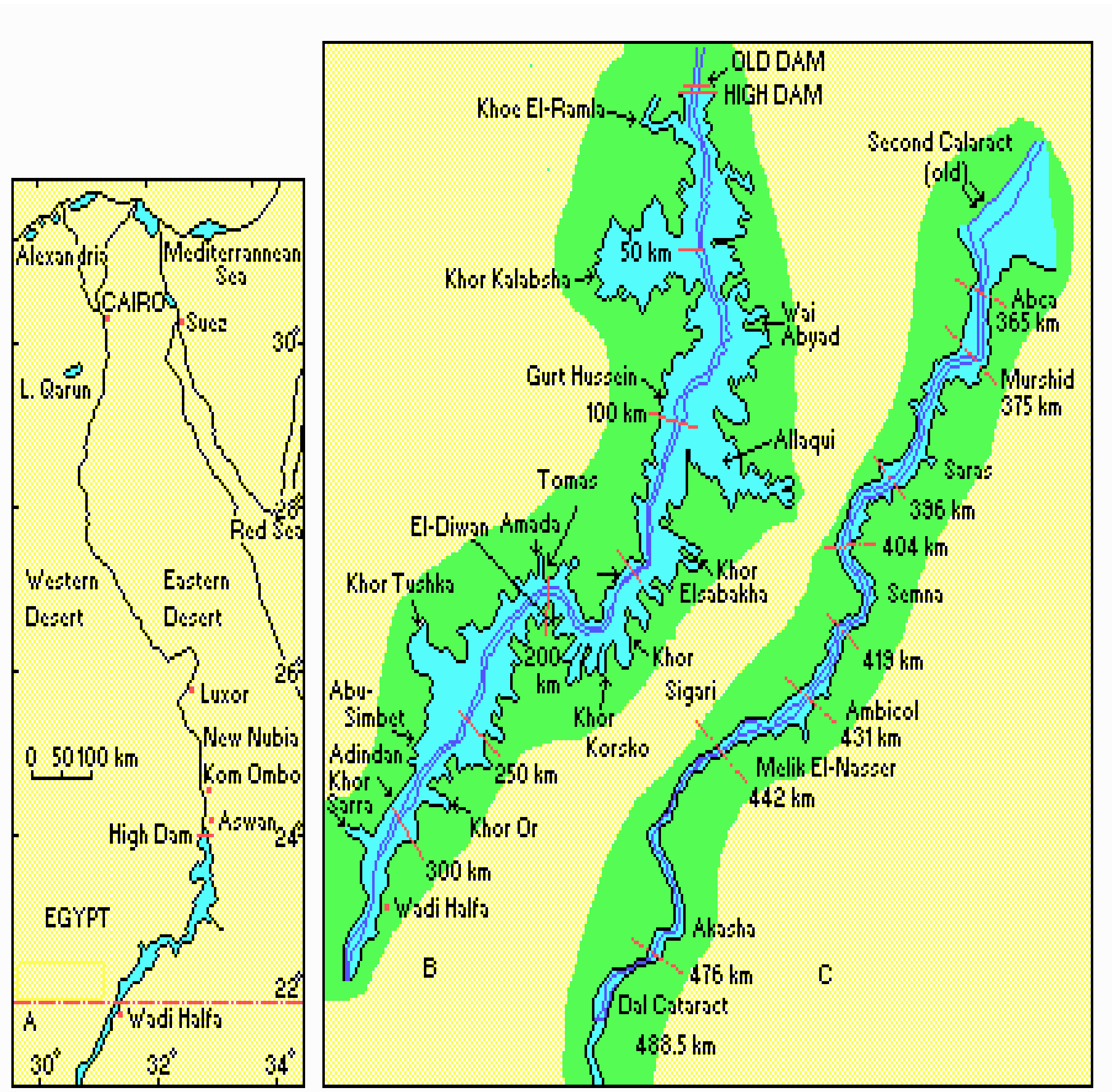

Fig (33) Location and Extent of Aswan High Dam Reservoir

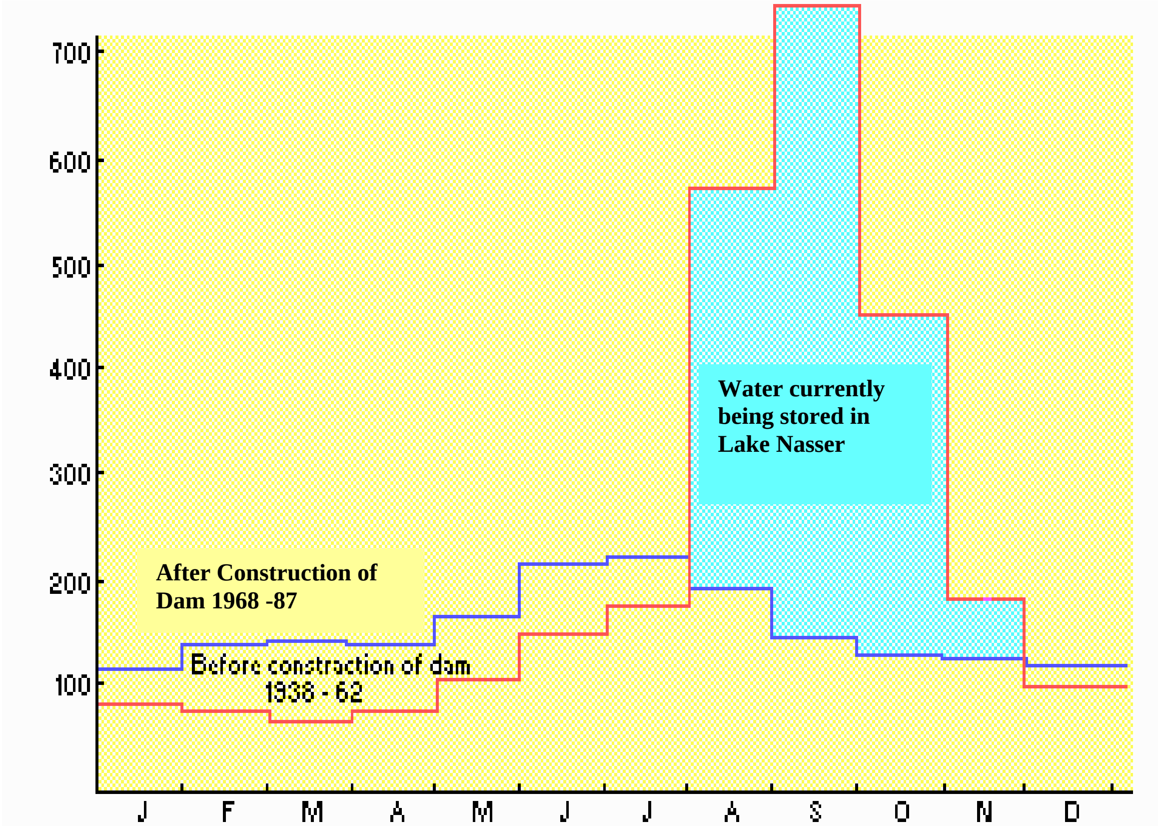

Fig. (34) Monthly Average Discharge (Million m^3) Downstream AHD Reservoir Before and After Construction

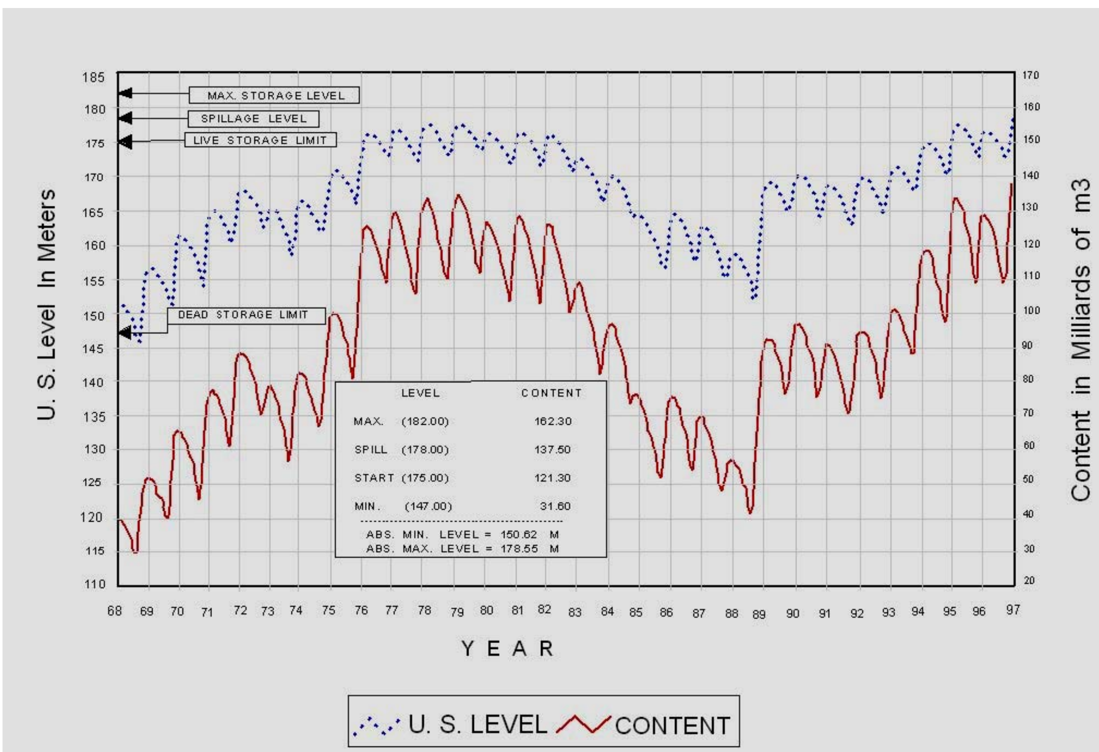

Fig. (35) U/S Level and Content of High Aswan Dam

Sediment distribution in AHD is investigated regularly along the fixed 21 cross-sections, Fig (36). Extensive bathymetric survey is conducted along the fixed cross-sections to give the profiles of the reservoir. Investigations and analysis for sediment deposition both upstream and downstream AHD has been carried out since 1973. The water levels are oscillating between 152 to 182 masl. The storage capacity of the reservoir is162 billion m^3 divided into three zones: dead storage capacity of 31.6 billion m^3 between levels 85 and 147 masl, live storage capacity of 90.7 billion m^3 from level 147 to 175 masl, and flood protection capacity of 39.7 billion m^3 for levels ranging between 175 and 182 masl (the maximum level of the reservoir), Table (8).
The Nile discharge before the construction of AHD peaked to over 700 million m^3 per day during the flood season. The latter value has been significantly reduced by the dam's construction to an average value of around 190 million m^3 per day distributed almost equally over the year, Fig (34).

Table (8) Storage Capacity of AHD Reservoir

Storage	From level (m)	To level (m)	Storage capacity billion m^3
Dead storage	85	147	31.6
Live storage	147	175	90.7
Flood control storage	175	182	39.7
Emergency flood control storage	182	183	7.0
			169

The Ministry of Water Resources and Irrigation (MWRI) of Egypt carries out sediment investigations three times a year, before, during and after the flood period. The measurements cover a distance of about 220 km up to the tail zone of the backwater curve (behind which no sedimentation is observed), Fig. (36). It can be noticed from the historical records that the sediment concentration decreases from 3000 ppm to just around 40 ppm, before and after AHD respectively. Fig. (37) and Plate (10) show the longitudinal profile and suspended sediment distribution along AHD reservoir. The total deposited sediment volume is estimated to be 2.5 billion m^3 in the period 1964-1995. This reflects that the average rate of sediment deposition annually is 140 million m^3 i.e. the rate of sedimentation is 0.1 %. It has been noticed that almost all the sediment deposition occurs in the Nile reach between 345 km and 430 km south of the dam site. In this region, sediment has already deposited in the live storage zone as shown in Fig. (38). However, several studies showed that until 1973, 99.98% of sediment was deposited in Lake Nubia. Available data suggests that suspended sediment dominates the total sediment in transport, which account to approximately 90% of the total sediment load. This means less than 10% is left for the bed load. Table (9) gives a mean annual suspended sediment inflow over the period 1965/66 – 1977/78 as 103 million tons. If we assumed all the suspended sediment is deposited in the reservoir plus 10% for the bed load (10 million tons), hence the expected life span of the AHD is over 1000 years. However, the dead storage requires about 200 years to be filled, but unfortunately most of the sediment if not all is deposited in the live storage, which slightly reduces the function of the dam.

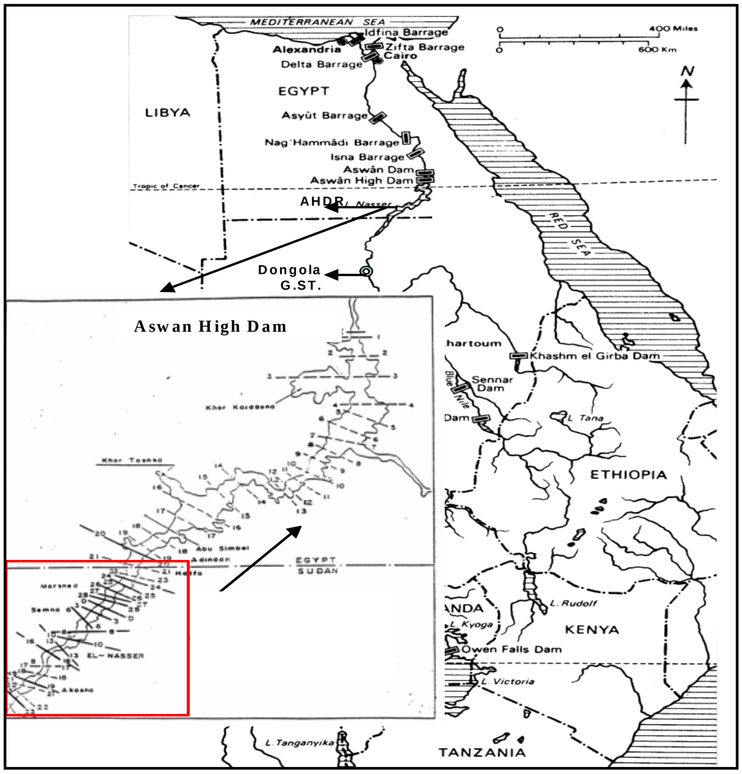

Fig. (36) Bathymetric Survey Cross Sections – AHD Reservoir

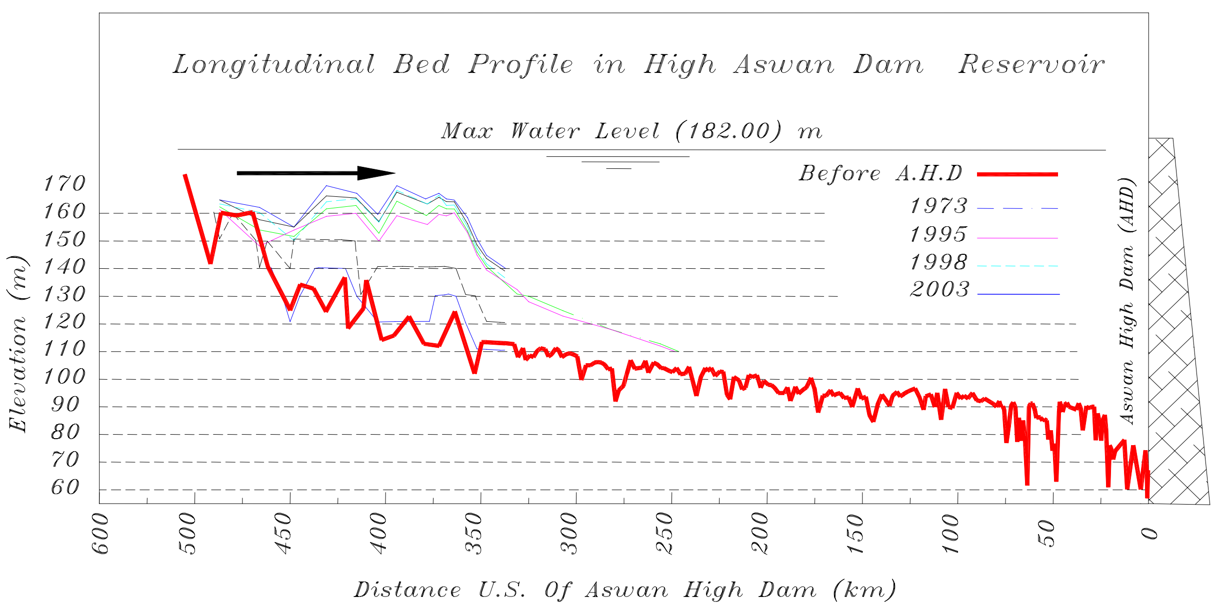

Fig (37) Longitudinal Bed Profile in AHD Reservoir

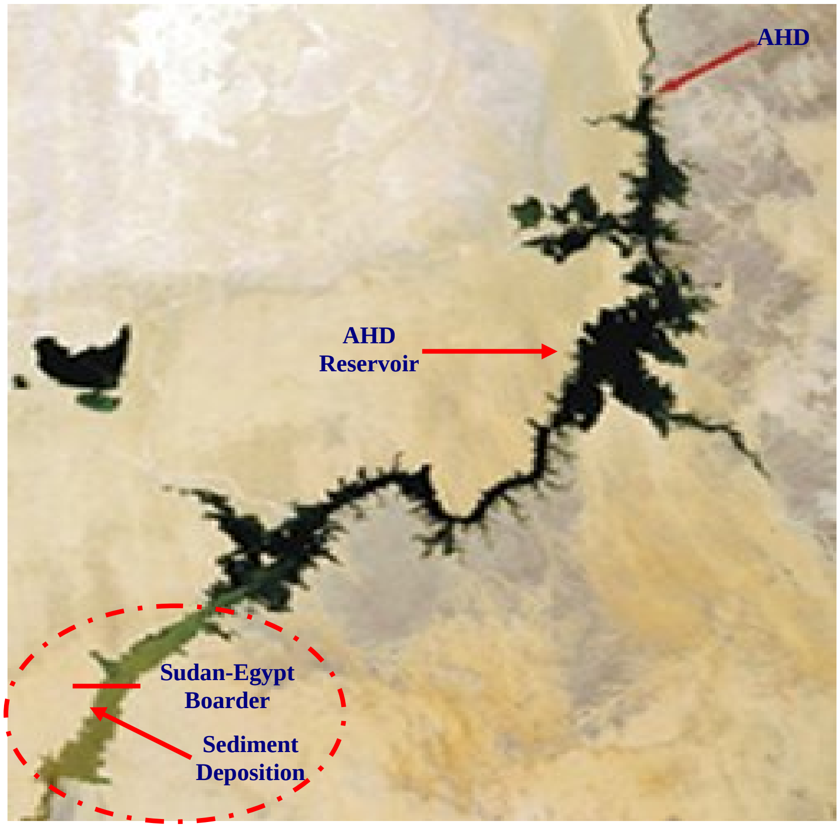

Plate (10) Sediment Distribution at AHD Reservoir

Table (9) Sediment Retention in AHD Reservoir [Million tons], 1982

Year	SS Inflow	SS Outflow	SS Depositing
1965/66	92.8	5.7	87.1
1966/67	75.9	3.8	72.1
1967/68	136.8	3.1	133.7
1968/69	80.7	2.3	78.4
1969/70	94.3	1.9	92.4
1970/71	114.1	2.7	111.4
1971/72	111.3	2.5	108.8
1972/73	47.2	2.7	44.5
1973/74	95.0	2.8	92.2
1974/75	128.0	2.8	125.2
1975/76	181.7	1.8	179.9
1976/77	81.0	1.6	79.4
1977/78	99.7	2.2	97.5

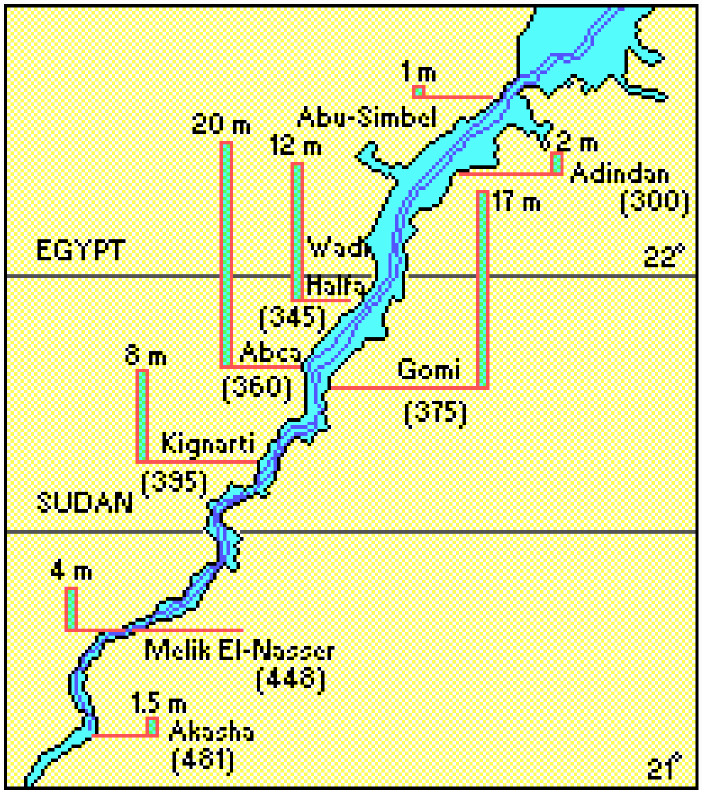

Fig (38) Distribution of Sedimentation Depth in AHD Reservoir (m)

It can be noticed that sediment deposition started at the tail zone of the reservoir and steadily progresses northward along the river bed. Several research studies suggest that the dead storage capacity was estimated to be sufficient to accommodate sediment load (130 million m^3/ year) for 300 to 500 years. It has been proved that the characteristics of rocky-narrow channel of the southern part of Lake Nubia work as a place for a new delta formation on the sides of the lake. However, almost all the sediment load reaching the AHD reservoir deposited in the live storage. A number of estimates of the potential life span of Lake Nasser located in Egypt and Sudan was published, raging from 20 years to over 1500 years, Makary (1982). The time forecasted for filling the reservoir by sediment deposition is estimated by MWRI to be 362 years, which is less than the original design life span of 500 years.

AHD as the second largest artificial Lake in the world has its positive and negative impacts on the region and the socio-economic development of Egypt in particular.

i- Advantages

- Full control of the Nile flow at Aswan in the far south of Egypt;
- Regulation of the discharge downstream of the dam to match the actual water needs for different requirements of Egypt.
- Protection of the Nile Valley and Delta from high floods and drought hazards that could persist for several consecutive years, (e.g. the drought during the eighties).
- Generation of cheap and clean hydroelectric power, (2000 MW).
- Realization of horizontal land expansion by reclaiming new lands, i.e. agriculture intensification and diversification.

- Change in the system of basin irrigation (one crop per year), to perennial irrigation (two or more crops per year);
- Improvement of navigation through the Nile and navigable canals; and
- Great flexibility in agricultural planning, crop patterns and intensified agriculture.

ii- Disadvantage

- The Nile delta is becoming smaller, because the Nile is no longer carrying any sediment downstream from the dam. The pebbles and sediment get stuck behind the dam. Wildlife is losing its home because the delta is shrinking in size.
- There has been accelerated desertification because farmers are abandoning fields with very low production.
- The rapid sedimentation near the head of the reservoir may dam up the narrow Nile valley in Nubia in a relatively short time. Therefore, the erosion increased along the lower Nile courses and the transgression of the Nile delta on the Mediterranean coast is taking place.
- Degradation of downstream river bank due to the clear water.
- Increase of groundwater table level causes root rottening of the crops.
- High evaporation from the huge surface area of the reservoir.

To summarize this section, Table (10) shows the sedimentation impacts on a number of the Nile dam reservoirs.

Table (10) State of Sedimentation in the Selected Reservoirs

Reservoir	Year of Construction	Original Capacity (million m^3)	Estimated Loss %	Mean Annual Rate of Sedimentation
Sennar	1925	930	71 %	8 Mm^3/yr
Koka	1960	1,650	32 % (1999)	13–20 Mm^3/yr
Roseires	1966	3,300	40 %	33 Mm^3 /yr
Sham ElGirba	1964	1,300	60 %	49 Mm^3/yr
Angereb	1986	5.28	50 %	0.125 Mm^3 /yr
AHD	1970	162,000	3 %	140 Mm^3/yr

Chapter Six

Future Dams on the Nile River System

6.0 Dams under Construction

6.1 Merowe Dam Reservoir

Merowe dam is considered the largest dam in Africa under construction today. Its actual cost of construction may exceed 2.0 billion US$. It is Located 800 km downstream of Khartoum on the Main Nile river in Sudan. Merowe dam will submerge the Fourth Cataract of the Nile and form a 200 km long artificial lake. Monenco (1993) estimated the storage capacity of the reservoir at level 298 masl as 11.05 billion m^3 equivalents to a pool reservoir surface area of 724 km^2. The low supply level (290 masl) corresponds to 476 km^2 surface area and 6.17 billion m^3 i.e. live storage of 4.88 billion m^3 would be available. However recently it was decided to raise the full supply level to 300 masl, which correspond to a storage capacity of 12.4 billion m^3. The dam is 67 m high with 1250 MW hydropower generation capacity, which will be completely installed by 2009.

The sediment data availability in Merowe area is limited; however, suspended sediment information was recorded at an upstream location on the Nile river from 1929 to 1964, prior to the construction of AHD (1960 – 1970). Limited sampling of sediment was carried out during the flood seasons in 1971 and 1990. Estimates of sediment from Monenco, (1993) study indicated average suspended sediment load into Merowe reservoir as 134 million t/yr for the period 1929 to 1964, 121 million t/yr in 1971 and 181 million t/yr in 1990. Monenco (1993) added 25% to the estimated suspended load as bed load, which resulted in 180 million t/yr total sediment load received by Merowe reservoir. It was then concluded that over 50 years after the project implementation the total deposited sediment into the reservoir will be 4.24 billion m^3.

Fig (39) shows the ten-day flows and suspended sediment loads of the Nile at Abu Hamad gauging station upstream Merowe dam during the 1990 flood season. It indicates that the sediment concentrations dropped from 11570 ppm in early August to less than 4000 ppm by mid of Sept. This leads to adopt similar procedure to what is happening in Roseires reservoir regarding the operation approach, where the initial flood season inflows are passed downstream with large amount of sediment loads, i.e. maintaining a lower reservoir level during this period. Based on applying the Burnes method for trap efficiency, Lahmeyer (2005) estimated the trap efficiency of Merowe reservoir to be 84%. However, it is evident that the bed load will be totally trapped by the dam. Several studies estimated 15% for the bed load to be added to the suspended load. Cristain et al (2006) reported that within less than 150 years the total storage capacity (dead and live) of Merowe reservoir will be lost, while the AHD can go up to 1000 years. Conservative figure was produced by Lahmeyer (2005) which expected 4238 million m^3 to be deposited in Merowe reservoir in 50 years time. However, according to the available information, 6500 million m^3 is going to be lost in 50 years time i.e. more than 50% of the total storage capacity, which is 5% more than the dead storage capacity of the dam. This means that 5% is lost from the live storage. Therefore, Merowe reservoir is going to face serious sedimentation problems by receiving sediment load for both rivers (Blue Nile and Atbara river). On the other hand AHD is going to benefit a lot from Merowe in many ways, e.g. reducing the sediment reaching AHD, acting as extra storage facility and impact on evaporation reduction.

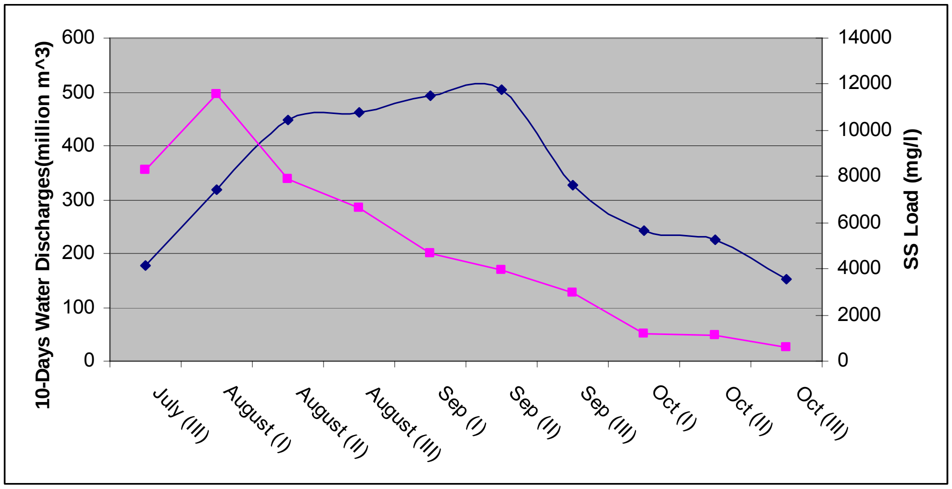

Fig (39) Suspended Sediment Load of the Main Nile at Abu

6.2 Tekeze Dam Reservoir

Tekeze dam is located in northern Ethiopia on one of the main tributaries of Atbara river (in Ethiopian called Tekeze river). Tekeze scheme hydropower project generates 300 Mw from 180 m dam height. The total storage capacity of Tekeze dam is 9.2 billion m^3. In his study Aforki (2006) reported that 40% of the reservoir storage capacity is provided as a room for the sediment inflow throughout the 50 years design life time of the dam. Therefore the dead storage is about 3.7 billion m^3. Hence the rate of sedimentation expected annually is about 75 million m^3 i.e. less than 1%. The sediment data in the feasibility study report of the dam is limited; hence the rate of sedimentation of Tekeze reservoir still remains unpredicted. According to several studies carried out in the Tigray area the rate of sediment yield is almost double the above reported value. Aforki (2006) tried to construct what he called "Tekeze Sediment Monitoring Program (TESMOP)". No doubt the sediment load in Tekeze river is large compared to other Nile basin systems, since it falls within a dry area with torrential rainfall during short period (July- Sept). For many reasons the author of this report believes that Tekeze reservoir is expected to be filled by sediment in less than the suggested period in the feasibility study. This is expected not to exceed 25 years. Aforki (2006) concluded his study with three different scenarios for the reduction of the sedimentation in Tekeze reservoir through flushing (i) Empty drawdown; (ii) Partial drawdown and empty drawdown but after the dead storage is filled; (iii) Four hydro- suction pipes options with different diameter (300mm; 600mm; 900 mm and 1200mm). He explained that the latter scenario was tested and proved to be effective. The dam will start generating electricity by the end of 2008. Plate (11) shows Tekeze dam under construction.

Plate (11) Tekeze Dam

6.3 Examples of Large Dams Planned on the Blue Nile

Four large-scale dams and reservoirs for hydroelectric power along the Blue Nile river within Ethiopia were proposed by US Bureau of Reclamation (USBR) in 1964, Fig. (40). Karadobi dam reservoir would be located just upstream of the Guder river confluence, approximately 385 km downstream of Lake Tana, and would be responsible for controlling a draining area of nearly 60300 km^2. The Mabil dam would be sited 145 km further downstream and 25 km downstream of the confluence with the Birr river. The Mendaya and Border dams would be constructed about 175 km and 21 km upstream the Sudanese-Ethiopian Border.

Table (11) provides more information of the four dam's characteristics as reported by USBR (1964). However, more recent studies changed the storage capacity of Mandaya to 49.2 billion m^3 and Boarder dam to 13.3 billion m^3 instead of 11.1 billion m^3, while Mabil dam is cancelled, Table (12). Moreover, there is a potential of hydropower generation in Beko Abo.

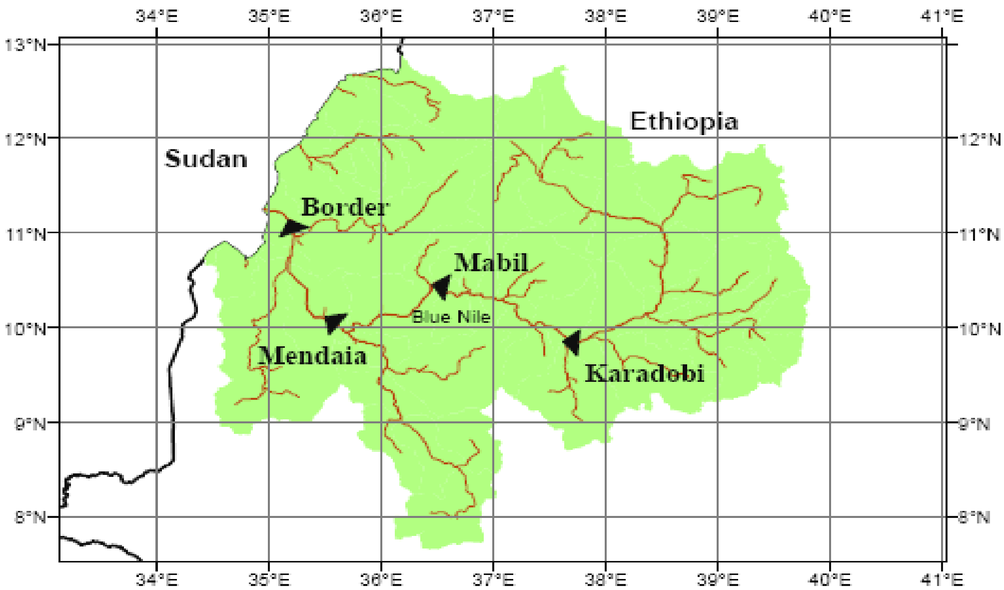

Fig. (40) The Locations of the Ethiopian Proposed Dams on the Blue Nile

Table (11) Characteristics of Potential Hydropower Projects on Blue Nile

Site	Dam Height (m)	Full Supply Level (m)	Gross Storage ($m^3 \times 10^6$)	Installed Capacity (MW)	Energy Output (GWh/year)
Border	84.5	575	11,074	1400	6200
Mandaya	164	741	15,930	1620	7800
Mabil	171	906	13,600	1200	5314
Karadobi	250	1146	40,200	1600	9708

Table (12) Characteristics of Proposed Hydropower Projects on Blue Nile

Site	Dam Height (m)	Full Supply Level (m)	Gross Storage ($m^3 \times 10^6$)	Installed Capacity (MW)	Energy Output (GWh/year)
Border	90	580	13,300	1200	6011
Mandaya	200	800	49,200	2000	12,119
Beko Abo	110	906	na	800 - 1000	na
Karadobi	250	1146	40,200	1600	9708

6.3.1 Karadobi Reservoir

Table (13) gives Karadobi dam key characteristics as reported by Norpln et al (2005). It will be the second largest dam in the whole Nile system after the AHD if it is constructed on the Blue Nile. It is expected to generate 1600 MW from total gross head of 236m. The gross storage capacity of Karadobi reservoir is 40.2 billion m^3. Norplan et al (2005) estimated the total sediment inflow to the Karadobi reservoir to lie in the range between 70 – 115 million t/yr. The latter are produced from sediment yields of 720 t/km^2/yr and 1150 t/km^2/yr rates from the catchment.

In their feasibility study of Karadobi dam Norplan et al (2005) concluded within the first 50 years the majority of sediment would be deposited in the non-active storage zone. It is generally believed that what has been reported in Karadobi dam feasibility study was based on very limited sediment information. Therefore, further study based on reliable and consistent time series sediment data is required in order to reach a technically sound estimate of sediment both in terms of quantity and as well as distribution within Karadobi reservoir. Lessons should be learned from the Roseires reservoir design which was based on very limited sediment information.

Table (13) Key Data for Karadobi Dam Project

Catchment	Area	82230	km^2
	Elevation site	910	masl
	Elevation maximum	4230	km
	Main river length	390	km
	Main river slope	2.2	m/km
Rainfall	Catchment	1300	mm/a
	Site	1000	mm/a
Evaporation	Reservoir (gross)	1460	mm/a
	Reservoir (net)	660	mm/a
Inflow	Mean (1954 – 2003)	649	m^3/s
	Driest year (1972)	402	m^3/s
	Wettest year (1998)	969	m^3/s
	Mean runoff	249	mm/a
Sedimentation	Specific yield (low/high)	720 / 1150	Ton/km^2/yr
	Annual inflow (low/high)	71 / 113	MT/a
(250 m dam)	Reservoir (50 year low/high)	3060/4870	Mm^3
	Storage loss (50-year low/high)	7.6 / 12.1	%
Power and Energy	Total rated output from 8 units	1600	MW
Hydrologic Data	Abay river catchment area upstream of Karadobi dam	66910	km^2
	Mean river flow at Karadobi dam site	649	m^3/s

	Annual mean peak flood PMF(probable Maximum Flood)	4500 30000	m^3/s m^3/s
Reservoir	Full Supply level (FSL) Minimum Operation level (MOL) Total volume at FSL Active reservoir volume Surface at FSL Extension of reservoir towards upstream	1146 1100 40200 17000 445 150	masl masl million m^3 million m^3 km^2 km
Dam	Type of dam (Roller Compacted Concrete (RCC)) Dam crest revelation Maximum height of dam above foundation	Gravity 1150 260	dam masl m

6.3.2 Mandaya Hydropower Dam

The proposed Mandaya dam site is located about 175 km upstream the Sudanese-Ethiopian boarder in the lower part of the Blue Nile catchment in Ethiopia. The Mandaya site is mountainous with upstream valley narrow and a steep sited gorge of up to 1500 m depth below the surrounding plateau. At that site the river bank is 310 m high over its bed (590 to 900 masl). Elevations rise to 2000 masl in hills on the right and left banks upstream, ENTRO (2007).

From Table (14) it can be noted that at Mandaya dam site the Blue Nile flows is in average 1014 m^3/s (41 billion m^3) annually i.e. about 80 % of the total Blue Nile flows at ElDeim station at Sudanese-Ethiopian Border. The storage capacity of Mandaya reservoir is 49.2 billion m^3, i.e. about 10% more than the inflow. However, ENTRO (2007) reported that Mandaya storage capacity is 154 % of the mean annual runoff of the Blue Nile at that point i.e. 54% more than the inflow. The present storage capacity is three folds of what has been proposed by USBR (1964).

Table (14) Summary of Adopted Flow Series for Hydrometric Stations & Project Sites

Site	Catchment Area (km^2)	Mean Annual Flow (Natural) (m^3/s)	Mean Annual Flow (with Beles Diversion) (m^3/s)
Kessie	65,784	517	440
Karadobi	82,300	649	572
Mandaya	128,729	1091	1014
Border	176,918	1547	1547
ElDeim		1547	1547

Based on a limited scattered sediment data, ENTRO in their Eastern Nile Power Trade Program Study (2007) concluded that Mandaya reservoir would lose some 40% of its gross storage capacity through sediment deposition within 50 years if not reduced by watershed management or if Karadobi dam is not constructed (upstream) and traps a considerable amount of sediment. ENTRO (2007) based their calculation by assuming the density of sediment deposits as 1.5 tones/m^3. However, if we adopt the most common density of 1.12 tones/m^3, Mandaya reservoir is going to lose more than 50% of its storage capacity in 50 years. Table (15) gives the estimated sediment discharge at Mandaya dam. Table (16) shows the increasing pattern of sediment loads over the period 1960 to 2004. This is likely attributed to the increase of the population and agricultural pressure, besides the overgrazing within the catchment. It is expected that this trend to increase by time unless proper watershed management is adopted.

ENTRO (2007) expected if the present trend of 2.6% per year of sediment discharge rate is continued, the sediment discharge could reach 700 million t/yr by 2050. According to ENTRO the sediment discharge rate is 2.4 more than what was reported in Karadobi feasibility study report (2006). The author of this study believes that the limited information on the sediment in the Blue Nile leads to un-authoritative conclusions. Therefore, it is high time for both Ethiopia and Sudan to draw more attention to this important issue for the sake of their future. Even Egypt although it has good information at AHD, we believe it should join efforts, since it is going to benefit from any upstream development especially the proper watershed and sediment management.

Table (15) Estimated Sediment Discharge

Location	Catchment Area (km_2)	Specific Suspended Sediment Discharge ($t/km^2/yr$)	Average Sediment Load (million tons / yr)
Kessie	68,074	2,791	220
Incremental catchment area Kessie to Mandaya	60,655	900	65
Mandaya	128,729		285

Table (16) Sediment Load at Mandaya Dam 1960- 2004

Item	*1960 – 1961 Data*		*1985 – 1995 Data*		*2004 Data*	
	Specific Sediment Discharge ($t/km^2/yr$)	*Average Sediment load (million tones/yr)*	*Specific Sediment Discharge ($t/km^2/yr$)*	*Average Sediment load (million tones/yr)*	*Specific Sediment Discharge ($t/km^2/yr$)*	*Average Sediment load million tones/yr)*
Suspended sediment	***901***	***59.3***	***836***	***55.0***	***2.791***	***183***
Bed load (20%)		***11.9***		***11.0***		***37***
Total sediment discharge		***71.2***		***66.0***		***220***

Chapter Seven

Sediment and Aquatic Weeds

7.0 Nile Basin Reservoirs Sediment and Storage Capacities

The present effective storage capacity of Sudan (3.0 billion m^3) represents only 15% of the Sudan share (18.5 billion m^3) in the Nile river waters according to the 1959 Nile Waters Agreement, while for example Egypt storage capacity is almost three folds its share in the Nile river waters (55.5 billion m^3), since the AHD storage capacity is 162 billion m^3. However, the rest of the Nile Basin countries storage capacity from the Nile waters e.g. Ethiopia and Uganda is limited, and in the rest is almost null (this is not including the storage in the natural lakes and Sudd region). This limited storage capacity of Sudan has set back the irrigation sector since the sixties of the last century where the last large reservoir was constructed in 1966. However, recently the government started to construct the Merowe dam in the Northern State on the Main Nile with a capacity of 12.4 billion m^3 for hydropower generation. On the other hand the heightening of the Roseires dam will increase its capacity from 3.0 to 7.0 billion m^3, this was envisaged at the time of the commissioning of the dam in 1966, but is yet to be implemented. The latter situation of Sudan is hardly compared with other Nile countries, since most of them receive a reasonable amount of rainfall annually except Egypt.

There are several potential locations for hydropower generation on Atbara river, Main Nile and in the southern part of Sudan e.g. Setiet, Upper Atbara (Akarib), Elsabalooga, Kajbar, Dal, etc.... These projects should be implemented within the efficient utilization policy of the Nile river waters for national and regional benefits. On the Ethiopian Highlands several locations for large dams are proposed, especially on the Blue Nile, e.g. Mendaya, Kardobi and the Border dams. Each of these dams can store billions of m^3 and their main purpose is the hydropower generation. It is believed they have a positive impact on the downstream countries and increase of the Nile waters in general. These dams are going to be constructed in a wet area where the evaporation is far less when compared with AHD for example, which is situated in very dry area. The second important thing they will regulate the Blue Nile flows throughout the year. Thirdly, these dams will reduce the sedimentation rate downstream and hence long life for the downstream existing dam reservoirs. On the other hand, greater potential of proper dam sites in Lake Victoria region are possible and in the White Nile, especially in the Sudd area i.e. in the Central Watershed region, Fig. (2).

7.1 Sediment Control in Roseires and Khashm ElGirba Dams

Several measures are used to manage the sedimentation in the reservoirs worldwide. One of the most effective methods is to apply Regulation Rules to operate the reservoir taking into consideration how to get rid of the maximum possible quantity of sediment and pass it downstream. Drawdown, sediment sluicing during the rainy season and impounding only after the passage of the peak of the flood are the preferred methods to control sediment deposition in the Sudanese reservoirs. Both reservoirs are provided with low-level sluicing gates with discharge capacity comparable to river annual flood flows. In the case of hydropower generation in Roseires reservoir, low level sluices are intended to pass the bulk of the larger sediment particles which are presence during the flood season to minimize abrasion of the runner blades of the turbines.

Removal of the already deposited sediment is rather very limited for most of the reservoirs in the Nile. Occasional flushing is made in Khashm ElGirba reservoir. Sediment removal by dredging is regularly made in Roseires reservoir in front of the power house intakes before the following flood.

Fig. (41) shows the sediment volume and the content of the Roseires reservoir in the period (1966-1992). In the first ten years the drop in the capacity was 550 millions m^3 with a rate of 55 million m^3 per year. This represents 17% reduction from the total reservoir storage capacity and 90% of the dead storage capacity. However, from Table (7) it can be concluded that 76% of the dead storage had gone and 3% was lost from the live storage in the first ten years. This is attributed to that fact that the estimation on which the designer of the dam based his calculations for sediment deposition was not true (15 million m^3/ year). In the second period (1976-1981) the reduction in the capacity was 100 million m^3 with a rate of 20 million m^3 per year. In the period (1981-1985) the reduction in the capacity was 120 Mm^3 with a rate of 30 Mm^3 per year. However, a drastic increase in the sedimentation rate occurred in the period (1985-1992) with a rate of 60 million m^3 per year and a reduction of 427 million m^3. It can be concluded that up to 1992 the Roseires reservoir lost 1197 million m^3 of its original capacity (37 %) i.e. 100 % of the dead storage and a considerable part of the live storage. This may be attributed to the drought period which took place during the eighties from the last century. Moreover, the policy of the food security adopted in Sudan by increasing the irrigated area without taking any mitigation measures regarding the negative consequences on the reservoirs and the irrigation canal networks. Furthermore, the intensive irrigation during the period of the high sediment content (July-August).

Plates (12, 13) show the magnitude of sediment and debris problems in front of Roseires dam.

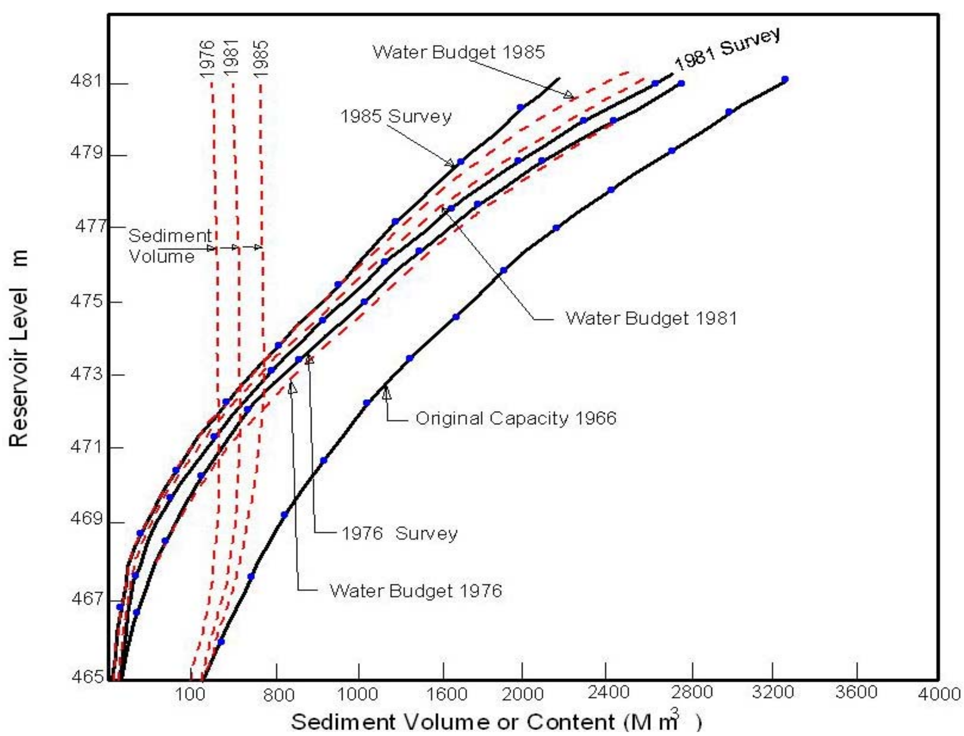

Fig (41) Roseires Reservoir Sediment Volume and Content (1964-1992)

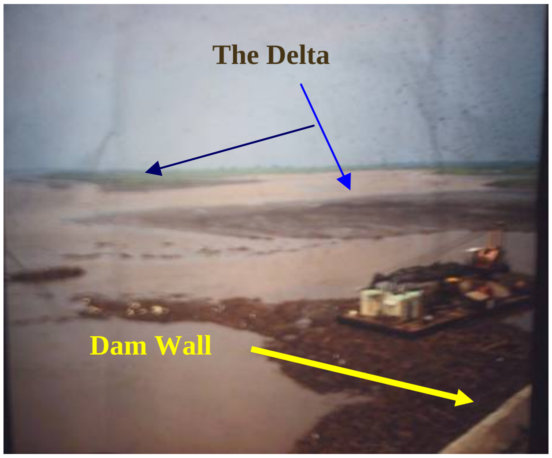

Plate (12) Delta Formation Upstream, Roseires Dam

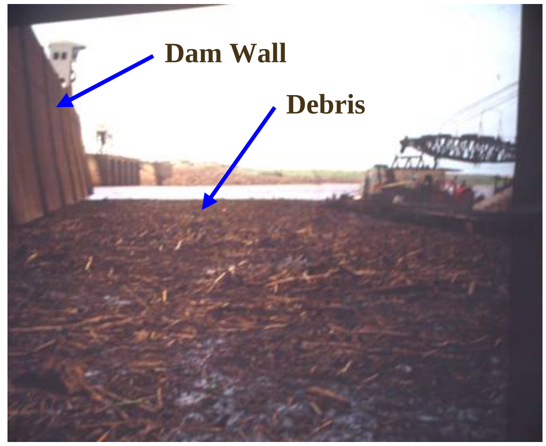

Plate (13) Debris in the Reservoir Upstream, Roseires Dam

7.2 Sediment and Aquatic Weeds Growth in Irrigation Systems

Sedimentation and aquatic weeds growth are the main reasons behind irrigation management difficulties and hence crop production reduction especially in Sudan. However, Egyptian irrigation is suffering from serious aquatic weeds growth after the construction of AHD, which absorbs all the sediment of the Nile in its reservoir and releases clear water. However, aquatic weeds are found on some of the tributaries of the Nile upstream Victoria Lake, damming the water flow and causing sediment deposition.

In this particular section we believe that the sediment bed load is not important since all of it is usually deposited in the reservoirs. Within the Nile countries Sudan is unique regarding irrigation management difficulties due to sedimentation and aquatic weeds growth interaction. Therefore, intensive sediment measurements were started in 1988 and 1996 to quantify the sediment entering two Sudanese large schemes (Gezira and Rahad irrigated schemes) respectively. Both schemes withdraw water from the Blue Nile which carries sediment with high concentration during the rainy season (July – Sept.).

The Hydraulics Research Station (HRS) of MOIWR carried out sediment concentration and discharge measurements in several locations of the Gezira scheme canalization system. It concluded that 5% of the sediment settled in the main canals, 22 % in the major canals, 33% in the minor canals and 40% passed to the farm fields. Plates (14 15) show the serious problems and difficulties created by sedimentation in the irrigated schemes in Sudan. The deposition of sediment in irrigation canals and its subsequent built-up of aquatic weeds results in losses of crop production in great magnitude. On the other hand, the impact of sedimentation includes loss of hydropower potential since method of sediment removal involves measures that lower the head and interfere with hydropower generator operation.

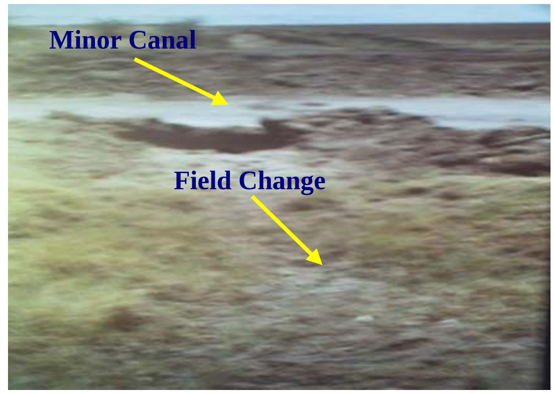

Plate (14) Inadequate Sedimentation Clearance of Irrigation Canal in GS

Plate (15) Irrigation difficulties in GS due to Sedimentation

The aquatic weeds growth is a serious problem in irrigation systems, especially during the winter time, where the irrigated water is clean without sediment and the environment is favorable for weed growth. Most of Sudan irrigation systems suffer from irrigation management difficulties due to this problem. However, the Egyptian irrigation system is even worse regarding the aquatic weeds in spite of the limited amount of sediment they receive after the construction of the AHD. Growth of aquatic weeds aggravates the sedimentation rate while the sediment depositions furnish good environment for weeds to grow. Ahmed and Ahmed (1993) reported that there are three types of aquatic weeds in Sudan irrigation systems, especially the Gezira Irrigated Scheme, namely: submerged, emerged and floating. Echinochloa Stagina (emerged) is the common species and is responsible for most of the irrigation difficulties. More than 60% of the operation and maintenance (O&M) costs of the irrigation management in the Sudan irrigated schemes goes to sediment and aquatic weeds clearance, Plates (16,17). Therefore, these two problems create many irrigation difficulties leading to water shortage and hence reduction in crop yields coupled with increase in the cost of O&M. However, many approaches have been implemented, Plates (16, 17), to mitigate this problem with a little success and many failures.

On the other hand, the hyacinth weeds in the White Nile started in 1957 (the Sudd area in the South of Sudan) disrupting river traffic, inlet channels and river life. It is now spreading all over the equatorial lakes requiring regional and international efforts to combat it. However, both sedimentation and aquatic weeds require joint efforts and cooperation between the Nile Basin countries. For example the problem of sediment, although it creates many difficulties and problems to Sudan, Plates (16, 17), it has its negative impact on the Ethiopian Highlands, from where it originates, degraded the land by erosion, and reducing its productivity.

Plates (16, 17) Clearance of Sediment in GS

7.3 Sediment Management in Gezira Scheme (GS)

GS the largest scheme in the world under a single management system is considered in this section as a case study.

Since the starting of the GS in 1925, de-silting and aquatic weeds clearance has always been needed to restore the canalization system, Plates (16, 17). The amount of annual sediment removal and its cost of removal are shown in Fig (42) for the period (1987 - 2005). In earlier years when the irrigation canals were in better conditions removal of 5 to 7 million m^3 of sediment was considered to be satisfactory, WB (2000). The process itself was carried out in a scientific method under the supervision of skilled engineers with high professional experiences. Hence the original canals L-sections were restored for most cases. In recent years the canals conditions have deteriorated to an extent they failed to satisfy the crop water requirements of the scheme. In 1999, a substantial canal de-silting program was carried out. According to the MOIWR records, Fig (42), 41.0 million m^3 of sediment had been removed from the GS canalization system. The author of this report believes that, what happened in 1999 is a turning point in the GS Sediment Mitigation Practices. It proved to be not realistic and not scientific. Therefore, the 41.0 million m^3 of sediment was factious and can't be accepted taking into consideration the past experience and the total amount of sediment entering GS annually. This shows how far the mismanagement of the irrigation system has gone, which at the same time reflects the lack of skilled personnel in the GS. If that value was true, it means that the canals were over-excavated and their cross-sections were widened. This is really a waste of the GS limited financial resources. Furthermore, it has led to a great damage to the whole canalization system. Hence the GS farmers will suffer from great water shortage and crop production reduction for many years to come. The following season (2000) the GS authority, in this respect MOIWR, removed more than 17.5 million m^3 of sediment i.e. in two consecutive years, the result was 5.0 m^3 of sediment per meter length of the whole GS canalization system were removed (known that the total length of the irrigation canalization system of the GS is estimated to be 11,000 km), which is impossible and not practical. Another reason which make the above values look unrealistic is the fact that only 6.0 million m^3 of sediment annually is expected to be deposited in the GS canalization system, according to the several studies carried out by the MOIWR – Hydraulics Research Station.

Such practices of sediment removal enlarge the debt burden, which is facing GS now, following many years of unprofitable performance. The total debt of the scheme reached more than 34 million US$ by the end of 1999 compared to the estimated annual revenue from Gezira agricultural activities (excluding livestock) equivalent to about US$ 46 million, WB (2000), while the total debt of GS in 2005 exceeded 150 million US$. This explains in clear terms the miss handling of the sediment management and its negative impact on the whole production of GS.

Fig (42) indicates a very strange phenomenon, while the water used in GS in 12 years (1987-1998) is almost averaging annually to 6.0 billion m^3; the removed sediment amount has never exceeded 14 million m^3 on average. However, a turning point was the year 1999 when the GS Authority declared its responsibility to perform the sediment removal from the GS canalization system itself, without having the know how and knowledge. The result has been drastic and damaging, where the sediment removal jumped to more than 41.0 million m^3 and in the following years (up to 2005) averaging to 25.0 million m^3, in terms of equivalent money it is more than 25.0 million US$ if we assumed 1.0 US$ per m^3 for sediment clearance. This is compared to the total average of sediment entering the GS every year according to many studies, between 7.0 to 10 million m^3. It is also noticed that the amount of water used and the cropped area in the last 6 years are less than the pervious period and hence reduction in the crops production, which indicates the continuation of declining trend. This can be generalized to some extend to other Sudanese large irrigated schemes, e.g. Rahad, Halfa and Suki.

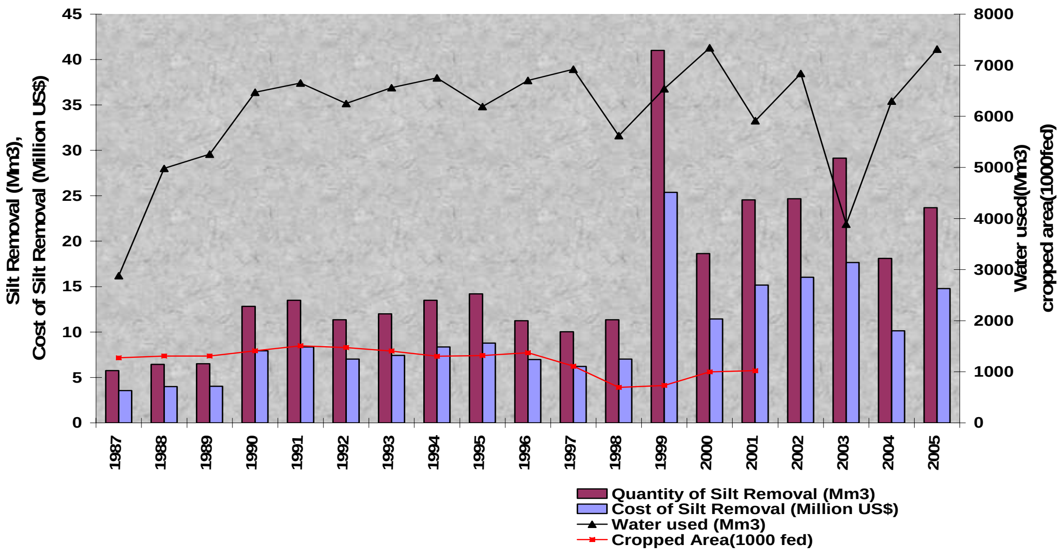

Fig (42) Amount and Cost of Annual Sediment Removal, Cropped Area and Water Used (1987-2005)

Chapter Eight

Economic Impact of Sedimentation

8.0 Economic Impact of Sedimentation

Recent research studies are focusing on developing new techniques to restore or prolong the life of the most threatened reservoirs. To justify the additional cost of a sediment control or storage recovery facility, an evaluation of the economic impact of sedimentation on agricultural irrigated schemes and reservoirs is needed. Sedimentation imposes many socio-economical and environmental impacts. Some of the negative impacts experienced can be summarized below:-

I) The upstream negative effects of reservoir sedimentation.
II) The downstream negative effects resulting from bed degradation or sediment deficiency.
III) Reduction in efficiency of power generation due to sedimentation hazard during flood season.
IV) The high cost of annual dredging in front of power intakes.
V) The consequences of storage loss.
VI) Irrigation pumps house (station) intakes, sedimentation and irrigation difficulties due to sediment deposition in the canalization systems.

Feasibility studies are usually economically justified based on the criteria that the benefit/cost ratio (B/C) exceeds unity. This is not compatible with sustainability, which would have project life extended for more than 50 years. Because the present value (PV) of a benefit far into future is negligible the result is that expense associated with features that would vastly extend the project life can not be economically justified, Hotchkiss (1994).

Basically, in the computation of damages caused by sedimentation, any of the three following standard methods may be used:-

i- The annual cost method;
ii- The PV method; or
iii- the capitalized cost method is a variation of the PV approach.

Siyam (2000) carried out an intensive analysis study adopting the PV approach, because the interest can justifiably be allocated to a sediment control facility. Hence, the economical loss is calculated based on the PV criteria and considered as a percentage of the total project cost. Therefore, two case studies are considered:-

i- Reservoir sedimentation, and
ii- Sedimentation in irrigation systems.

Siyam (2000) based his theoretical point of view on the total benefit that can be generated from a project equivalent to the total benefit generated from the repeated use of the storage volume during the economic life of the reservoir. The merit of this visualization is that, any reduction in storage can be transformed into a valued loss by using the well known discount rate formulae. Reservoirs with a capacity/inflow ratio greater than unity are considered.

In irrigated agricultural schemes cost-recovery fees that ensure financial viability of water entities are more realistic, and evidence suggests that farmers are willing to pay for a reliable supply of water, but the complexity lies in the task of collecting the fees.

8.1 Water Values in Irrigated Agriculture and Hydropower

To evaluate scientifically the economical impact of sedimentation a practical exercise is necessary. Sudan experience is rich and has been taken as an example. In the irrigated sector in Sudan, the method of water pricing has passed through various stages. Two of these methods are going to be discussed. In both the primary objective was to cover the expenses of operating and maintaining the canal network and pump stations. Over 60% of these expenses were devoted to the annual clearance of deposited sediment in canals during flood period.

In the first method, which is called the combined account (CA), the government of Sudan, the agricultural company and, the farmers share the net benefit from the sale of cotton in ratios of 40:20:40 respectively. The government takes the 40% from the net revenue of the cotton production in return for providing land and water to the farmers. The agricultural company takes 20% as management expenses and the remaining 40% goes to the farmers. The net revenue is calculated after deducting the total cost of production in all farms from the revenue of cotton sale. No other charge is taken from the farmers for the other main grown crops i.e. wheat, groundnuts and, sorghum. However, the farmers are obliged to follow a strict cropping pattern in which a certain area of cotton has to be cultivated every year.

The second method which is called the individual account (IA) was introduced in season 1980/81 following an advice given by the World Bank, Adam (1997). Some investigators believe this was a major mistake committed by the government at that time. As the name (IA) indicates in this method the farmers are treated individually with the intention to give them the incentive to increase their productivity. The disadvantage seen with CA is that unproductive farmers receive unworthy benefit as the production cost is shared among all farmers. However, the latter system had a positive impact on the sustainability of the irrigation system. The author of this report believes that the former method is better than the latter, since the experience in the following years proved that IA is a big failure. At the same time the irrigation system suffered a lot especially when talking about irrigation management and sediment clearance from the canals systems in time and space. CA has an advantage regarding the irrigation system sustainability by making funds available for operating and maintaining the irrigation networks. Another important point is that the problem of farmer location with respect to the irrigation system i.e. Head – Middle – Tail, is partially absorbed when CA is adopted rather than IA. In other words the equity distribution of the irrigation is one of the major problems of such a system. Fig. (43) shows the impact of the farm location, (with respect to the minor canal), on the crop production and net return.

Furthermore, the water charge is also altered and calculated per fad. (1 feddans = 4200 m^2 = 0.42 hectare) of the irrigated area. The fee changes with the crop type to reflect the water consumption, and varies from year to year to accommodate change in prices. Between 1981 and 1995 the water rates for cotton crop varied from US$ 4.4 to US$ 21.8 with an average of US$ 13.2 per feddans. For wheat it changes between US$ 3.4 and US$ 13.8 with US$ 9 per feddans being the average. Nowadays the water rates for all the crops are almost tripled.

In practice there have been institutional obstacles regarding the full implementation of the management systems, in particular the water fees collection, to achieve the objective goals. In 1995, a separate institutional body was formed within the MOIWR with the key objective to improve the irrigation performance in the GS through developing a method for pricing water and collecting water fees from the farmers. Moreover, it is to carry out the routine works of O&M of the irrigation canal networks and pump stations in a satisfactory way. Unfortunately, this body failed to do the job due to many reasons, which are beyond the scope of this report. It was dissolved in 1999 i.e. after an experience of four years, which is very short to judge its performance. However, the experience is worthy to be studied to gain the lessons out of it.

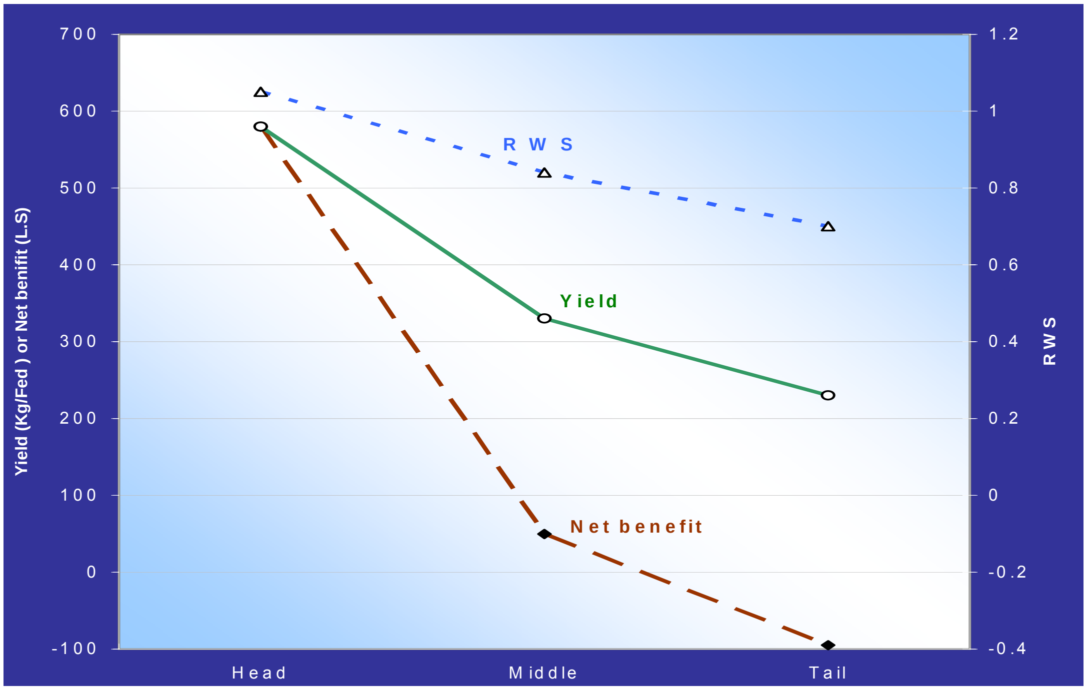

Fig. (43) Inequity in Cotton Yield, Net Benefit and Relative Water Supply (RWS) along a Minor in the Gezira Scheme

The misconception of not including operation and maintenance of the main infrastructure, i.e. dam/reservoir body into water pricing still prevails. In this particular case the author of this report could argue that the original cost of Sennar and Roseires dams are totally returned to the Central Government during the implementation of the Combined Account (CA), when the share of Government was 40 % of the total cotton crop production return, at least for the GS. In fact there exists another department within the MOIWR, whose responsibility is just to operate and maintain the national dams and reservoirs bodies. The main infrastructures are seen to be owned by the national government, which should operate and maintain them. The result is that sedimentation of reservoirs with its huge impact is not directly seen as financial loss by any of the main users of the reservoirs. This situation makes investment in sediment controlling facility financially not attractive, if ever justifiable. Fig. (44) shows that canal sedimentation and reservoir sedimentation occur at different times. Hence water pricing for different crops to be determined based on account of maintaining canals or reservoir sedimentation can be practically distinguished. However, an annual cycle would be the most logical approach where all the costs of canal maintenance and lost reservoir capacity were reflected in the pricing, Siyam (2000).

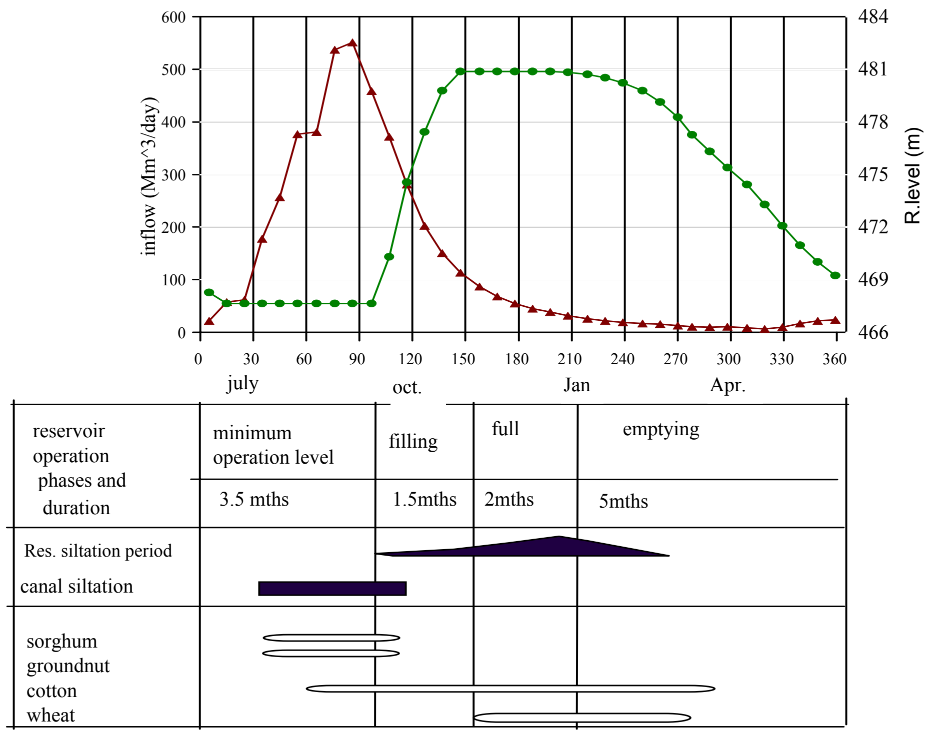

Fig (44) Roseires Reservoir Operation Curve and Plantation Periods of the Main Irrigated Crops

Siyam (2000) argued that the annual economical impact of the reservoir Siltation can be regarded as the annual avoided cost of thermal or diesel generated energy that would be required due to shortage in hydropower energy production as a result of sedimentation. Then, he concluded that the shortage is equivalent to the energy that would be produced if a volume of water equal to the silted volume would have been passed through the turbine.

It was reported that the average cost of fuel/kwh alone during 1980s and early 1990s was in the order of 0.065 US$, Sharfi, (1993), while the energy tariff is in order of 0.084 US$/kwh. For example in the Colorado river hydroelectric system, the short run cost savings provided by hydropower compared to coal-fired steam generating plants are US$ 31 per acre-foot and US$ 76 per acre-foot when compared to gas-turbine electric plant based on 1986 US dollar value, Siyam (2000). These are visualized as the additional cost of replacing lost hydropower production due to an acre-foot decrease in flow with a more expensive source of electricity, and can be thought of as short run marginal values.

The benefits from the Roseires reservoir are derived from its multi-purpose functions as the main provider for irrigation water, hydropower generation and flood detention. The reservoir also serves to augment low flows and to supply water for domestic use. On the other hand, cotton, sorghum, wheat, and groundnut are the main crops produced by the irrigated sector in Sudan. Except for the wheat all the crops are grown at the beginning of the rainy season June/July. Sorghum and groundnut are supposed to be harvested before the commencement of the dry period, while cotton continues to be irrigated until March. Wheat takes all its water during the dry period. Other crops sharing the dry season water are sugar canes, vegetables, forests, fodder and gardens. Here, cotton and wheat are taken to be the two major crops which can reflect the economical impact of sedimentation in the agricultural sector. The water requirement for wheat is determined to be in the order of 3300 m^3 per feddan and for cotton is 3800 m^3 per feddan during the dry season.

8.2 Economical Losses due to Sedimentation in Agriculture and Energy

Siyam (2000) assumed that the total net present value in 1966 of the economical revenues forgone due to sedimentation of the active storage of the Roseires reservoir as shown in Fig. (45) is a function of different discount rates. It is composed of the addition of the energy and the agricultural sectors revenues. The priority of irrigation over hydropower generation is well known in Sudan and clearly reflected in National Policy. This amount of losses with the impact on the former is being higher than the latter at all discount rates. Siyam (2000) concluded that the degree of impact from the economic point of view justifies the construction of another dam, similar in size to the Roseires dam, if the discount rate is in the range of 5 to 6%. In Fig. (45) the lost economic revenue is normalized by dividing by the original dam construction cost which was 75 million US$ in year 1966. At higher discount rate, such as 12%, the economical loss falls non-linearly to 20% of the original dam cost. This indirectly tells the amount of investment that should be devoted to sediment controlling facility if it has the capability of securing the active storage of the reservoir.

It was found that, a sediment control facility with capital cost as high as the cost of the total project would be economically justified if only the active storage of the reservoir would have been preserved. The total economical revenues forgone due to the active storage loss was found to vary non-linearly between 115% and 22% of the original dam cost when the discount rate varied between 5 and 12% respectively. When extra sediment- born losses were considered the percentage of revenues forgone has risen to 160% and 30% respectively. These losses were approximately shared equally between the two main users of the reservoir, the energy and the agricultural sectors. In simple terms Fig. (45) shows the total financial losses due to sedimentation of Roseires reservoir as a function of the discount rate and Fig (46) expresses the losses as a percentage of the original cost of the dam. The total financial losses varied non-linearly between 6% and 26% of the dam cost as the discount rate varied between 12% and 5% respectively. It also shows under the current assumption, that both energy and agricultural sectors have suffered equal financial losses due to sedimentation.

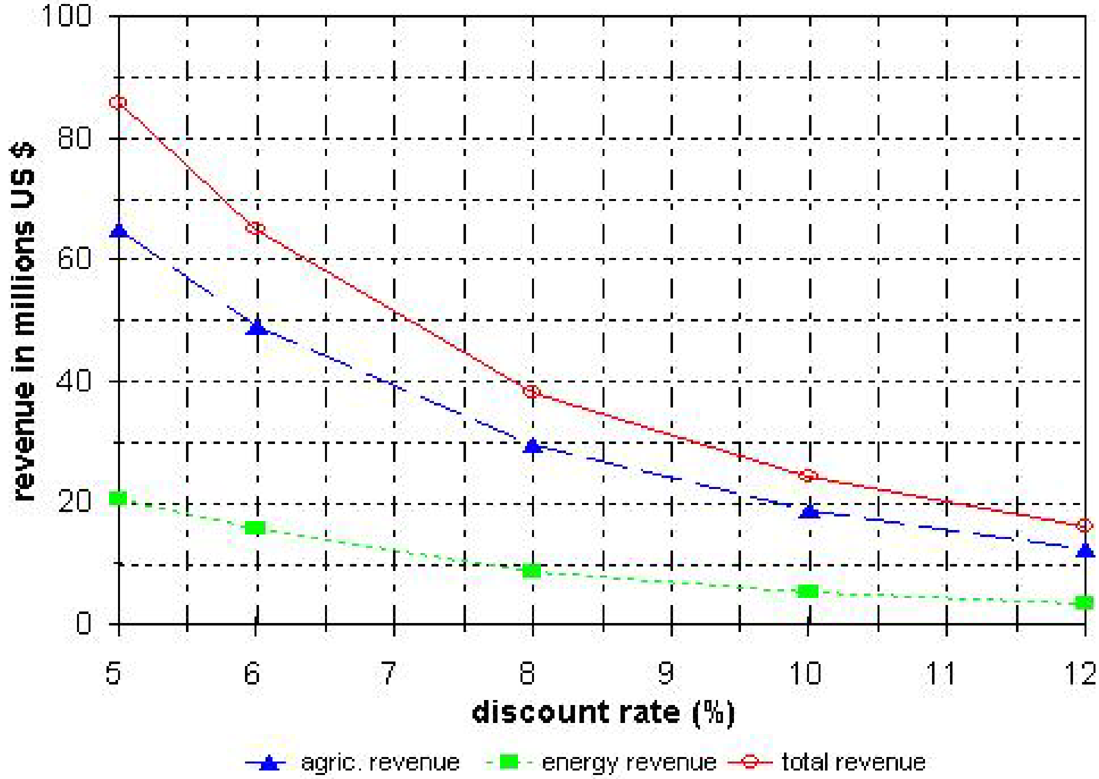

Fig. (45) Economical Revenues Forgone in Agricultural and Energy Sectors Versus Discount Rate

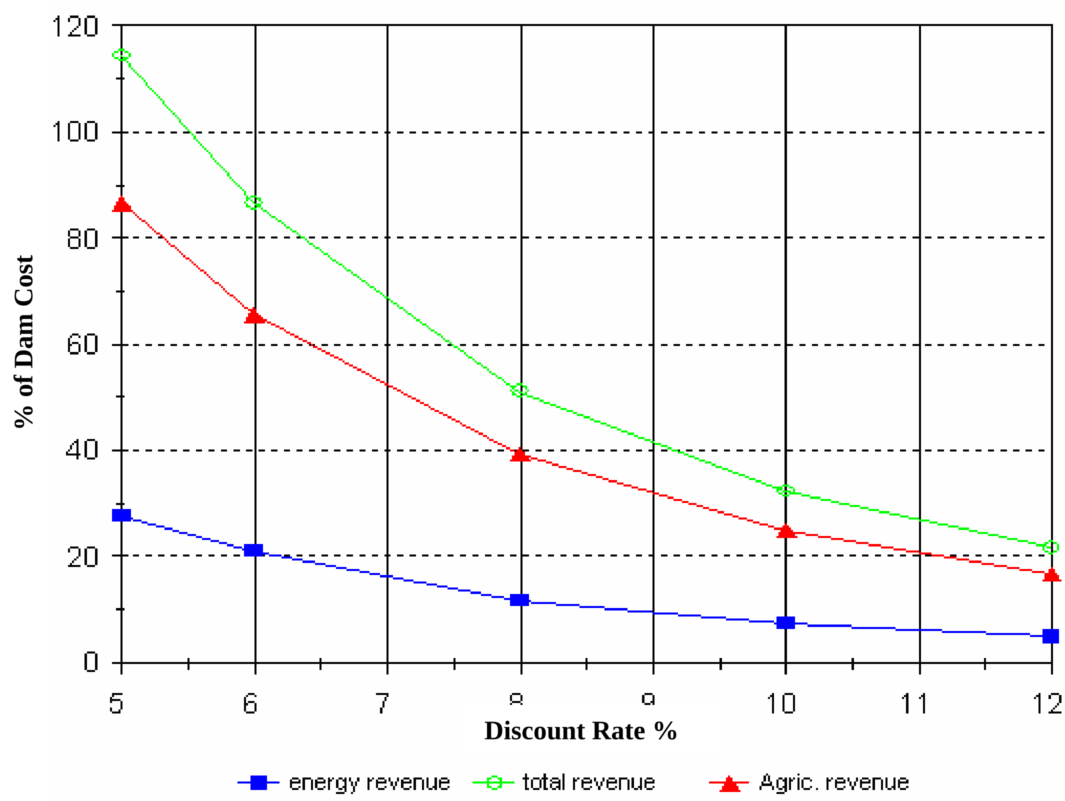

Fig. (46) Financial Losses as a Percentage of the Original Cost of the Dam

8.3 Sediment Socio-economic and Environmental Impacts

Sediment is socio-economic, environmental and geomorphologic resources, as well as, a tool of nature. However, changes in sediment quantity and quality can have a significant impact on a range of social, economic and environmental systems.

For example in GS traditionally, manual labour was used for weeds removal, but this practice has been abandoned due to health hazards (such as bilharzias). Excavators with special weed-cutting are used to remove weeds from the canals, but they face lack of funds for maintenance to keep them working i.e. the availability of proper equipments in time and space is highly recommended to alleviate such problem. Ahmed and Ahmed, (1993), concluded that narrow and deep canals may have positive effect in reducing the aquatic weeds growth by preventing the sunlight reaching the submerged vegetation. Moreover, high velocities are created in the canals in order to make water turbidity, which also prevents the sunlight to reach the vegetation. Therefore, the weeds volume to be removed will be reduced. Moreover, less aquatic weeds growth means less sediment deposition. Other means are also used to clear the aquatic weeds from the canals e.g. biological (special species of fishes), chemically (Roundup). The Gezira scheme was not favouring the chemical methods for many reasons, one of them the health hazards. Although the biological method was not effective, however is highly recommended to expand.

On the other hand, from a theoretical point of view, the total benefit that can be generated from a dam/reservoir project can be visualized as equivalent to the total benefit generated from the repeated use of the storage volume during the economic life of the reservoir.

The deposition of sediment in irrigation canals and its subsequent built-up of aquatic weeds results in losses in production of great magnitude. The sediment deposited in the GS canalization system and the farm fields is estimated to be about 1000 million m^3, since its establishment in 1925 up to now. If 40 % of the latter amount is evenly distributed throughout the farm fields, this means 500 m^3/feddan i.e. 120 mm depth of sediment. Taking into consideration this amount of sediment cannot be distributed evenly in the farms; therefore, the land leveling is disturbed, leading to serious irrigation difficulties. Moreover, these huge amounts of sediments taken out of the canals and placed on the canal banks create transportation difficulties by blocking the roads. This makes most of the roads adjacent to the canal not accessible. From environmental point of view the motion of cars or other machines when they pass through these roads will create dust foams and hence health hazards to the villages inhabitants and/ or farmers.

8.4 Domestic Water Uses

If the sedimentation is creating several management difficulties in the agriculture and energy sectors, it also has its negative impact on the domestic water supply, in the water treatment plants and the distribution networks.

The high turbidity (sediment concentration) of the Blue Nile and Atbara river water during the flood season causes difficulties in drinking water treatment plants, especially in large cities situated near the Nile system, e.g. Khartoum, Al-Damr. The turbidity of the Blue Nile during the flood season in some years reaches more than 23000 ppm. The latter leads to several problems: reduction in drinking water treatment plant capacity, pollution, inefficiency and problems associated with water delivery infrastructure and pumps. The result is only 50% of the residents have adequate access to safe drinking water in many cities using the Nile system for their water supply. This is based on consumption per capita in urban areas taken as 50 liters/day, which is far below the real need and WHO standard. Sudanese rural areas have on average less access; about 47% have access to safe drinking water, drops to 25% during the dry months of the year (January to June). The rural daily consumption per capita is taken as 18 liters/day. These low percentages of drinking water access in way or another is linked to the sediment treatment in the drinking water plants.

In most Nile Basin countries the domestic water will not exceed 12 % of the total water consumption, e.g. Sudan requires 8.0 billion m^3 by 2025, (2.5 billion m^3 for people drinking water and 5.5 billion m^3 for livestock and others). Therefore, attention should be given to the sedimentation problem when dealing with the Nile waters for domestic water use. Unfortunately, there is limited information regarding this particular aspect in spite of its importance. Therefore, domestic water treatment plants (design and O&M) require proper information on the Nile water turbidity concentration and its distribution. The mitigation measures which are implemented today are more or less chemical treatment. The latter is believed to be very dangerous to the health of the people drinking from the Nile water throughout the Basin.

Chapter Nine

General Concluding Remarks

9.0 General Concluding Remarks

The continuing landform development occurring over the earth surface necessarily implies the production and subsequent distribution of sediments. Sediment is the end product of erosion or wearing away of the land surface by the action of water, wind, ice, and gravity. Sedimentation process causes great problems worldwide by raising the cost of operation and maintenance and complicating the design of water structures. The problems linked to sediment create difficulties in managing water systems. Consequently, there is a need for clear understanding on how to improve the watershed management, soil loss tolerances and hence formulation of appropriate soil conservation strategies. .

No doubt the soil erosion, land degradation, sedimentation in the reservoir and the irrigation systems in Nile Basin, have environmental and socio-economic impacts. Therefore, as conclusions for this study “Sediment in the Nile River System”, the following remarks can be reported:-

9.1 General Remarks on the Hydrologic and Geomorphic Characteristics of the Nile River System

- The Nile River is sinuous river with highly dynamic behavior.

- Climate changes and human activities within the Nile river catchment can have detrimental effects on both sediment quantity and quality in the Blue Nile system.

- The nature of the hydrological graph of the Nile river system flow is unique, with a peak of up to 1000 millions m^3 per day (during the flood period July, August and September) in the rising limb and with less than 80 millions m^3 per day in the falling limb (recession period). This behavior makes the system very complicated and the morphological one is highly vulnerable.

- Many of the large international rivers such as: the river Nile, the Yellow River, Mississippi carry huge amount of sediment. The Fraser River in Canada carries an average of 20 million tones of sediment each year; the Nile River carries an amount that exceeds 140 million tones annually and the Yellow river in China carry an annual amount of sediment 1600 million tones, i.e. several times more than that of the Nile River.

- Natural geologic erosion takes place slowly over centuries or millennia. Whereas erosion that occurs as a result of human activities may take place much faster. Therefore, it is important to understand the role of each when studying sediment transport. About 1% of the world’s water storage capacity is lost every year through sediment deposition in reservoirs.

9.2 Remarks on Soil Erosion

- Agriculture expansion on steep slopes and loss of vegetation cover have accelerated geological rates of soil erosion which results in relatively high sediment rates delivery to the Nile river system, e.g. Ethiopian Highlands.

- The sand encroachment towards the Nile River course is a serious phenomenon where in some places most of the flood plains have been completely buried and its course is getting narrower. The erosion and bank failure are also considered serious problems, especially in the Northern Sudan, endangering the Nile River water course and all means of life in that area.

9.3 Remarks on Reservoir Sedimentation

- Sedimentation rate in the Roseires reservoir (the case study) is directly proportional to the square-root of the time in years.

- The existing Sudanese and Ethiopian reservoirs lost about 50% of their storage capacity in the last 40 years, AHD lost about 4% taking into consideration the total amount of sediment reaching the reservoir, about 140 million tons annually.

- The sedimentation rate in the last decade (1990s) increased rapidly, indicating that, there is a trend of increased in land degradation occurring on the upper Blue Nile catchment areas. Therefore, integrated sediment management is found to be the best policy to minimize the adverse impacts of the sedimentation within the entire Blue Nile River System.

- Large dams generally have extensive impacts on rivers, watersheds and aquatic ecosystem. One of the negative impacts of sedimentation in the reservoirs is that sediment deposition reduces the dam depth, and increasingly large proportion of the stored water is lost by evaporation. Evaporative losses are large in small dams, which typically have average water depths of only a few meters, and are located in regions where the evaporation rates range between one to two meters per year. This is well accepted to happen in all the dams constructed on arid or semi-arid region e.g. AHD, Merowe.

9.4 Remarks on Sedimentation Impact to Irrigation Schemes

- The regime concept for designing canals works well for main and major canals in the different irrigation schemes of Sudan. For minor canals a modified criteria was proposed to reduce sedimentation. To minimize sediment deposition in the irrigation systems it is recommended to use settling basin at the head of the main and major canals.

- Based on the GS experience it is important to satisfy the tail of the irrigation system first before the middle or head of the canals. This is the best way to operate the irrigation system properly and reduce the sediment deposition in the minor canals.

- Improper and inadequate O&M for sedimentation and aquatic weeds management, controlling hydraulic structures could lead to low crop productivity.

- Sediments settle at the bed of the irrigation canals reduces the carrying capacity and hence causes overtopping. It is usually cost effective to reduce the concentrations and size range of sediments entering canals with a sediment control structure than to rely on the process of silt removal in canals. However, based on GS analysis and interpretations, it is generally founded that most of the sediment load is a wash loads which is difficult to manage.

9.5 Remarks on Socio-Economic Impact

- Sediment has a socio-economic, environmental and geomorphological impact. Changes in sediment quantity and quality can have significant implications and impact on a range of social, economic and environmental systems.

- Sediment has various detrimental effects which include: degradation of water quality by pollutants, degradation of catchment, hampering of navigation, reduction of fisheries and aquatic habitat, deforestation and forestation, reduction of energy production, more agricultural problems, increased water supply problems…etc.

- Neglecting to manage sediment in a sustainable way, through adequate sediment management strategies or policies, could lead to a higher operational cost and significant adverse impact to society and environment. It is therefore important to evaluate the socio-economic and environmental impacts involved in sediment management.

- Sedimentation in Nile reservoirs and irrigation canals becomes a serious regional problem which requires immediate action (provision of adequate funds for O&M, research and development).

9.6 Remarks on Mitigation Measures

- There are three main options for alleviating sedimentation problems in reservoirs, namely (i) managing sediments within the reservoir by controlling water levels, (ii) reducing sediment inputs either by catchment conservation or by providing upstream storage, (ii) evacuating sediment from reservoir by sluicing or flushing.

- Mitigation measures for sand migration towards the River Nile and problems of bank erosion require both attention and prompt action to deal with them.

- The use of expensive sediment control structures, (e.g. sediment extractor), can be justifiable because it would accommodate the increase in the cropped areas and it could result in saving the cost associated with silt removal. Sediment control has two major benefits, firstly, it reduces the amount of desilting required, and hence costs of sediment removal, and secondly it improves the reliability of water supply to downstream parts of irrigation system, enabling the irrigated areas to be maintained. This has a positive impact on farm income, farm investment, productive capacity, and the long term success of the irrigation scheme.

9.7 Remarks on the Way forward for future research and better control of Sedimentation

- Many researches, studies, and theories have been developed to deal with sediment however; there is no consensus on a well defined procedure or approach to deal with sediment problems and their impacts.

- Worldwide relevant institutes, agencies and researchers in this field need to combine their effort and work in a more organized research programmes to deal with sediment. This is expected to help international communities achieve practical and effective solutions. Joint and coordinating effort entails partnership, pooling resources, focusing science, sharing of information and experiences. Besides, it helps build and strengthen the human capacity needed, it will also benefit the policy and decision makers as it would result in a more informed decisions.

- Capacity building is an essential requirement for efficient water resources management. The Nile Basin countries must give it priority consideration.

- Part of the sediment problem in the Nile river system can be solved through joint efforts between Sudan and Ethiopia. The sediment creates many difficulties and problems to Sudan, at the same time, it has its negative impact on the Ethiopian Highlands, from where it originates, degraded the land by erosion and reducing its productivity.

- There is a need for international support to irrigation and drainage research in the Nile Basin countries, especially those irrigate from rivers carrying sediment laden. Despite the great progress in irrigation research in developed countries, few of the results have found a place in the developing world.

- It is highly recommended to look into the current sediment removal practices and try to adopt more scientific technique.

- Suitable sedimentation management is a key for the sustainable water resources management. Sedimentation and aquatic weeds represent a great challenge to many irrigation schemes; therefore, integrated sediment management is the only way ahead.

- The key for improved sediment management is in the collection of accurate data and the interpretation and conversion of this data to knowledge.

- There is a need to review the operation of existing dams in the light of new dam construction at the upper watershed of the Nile. Example, in the event that a series of dam reservoirs are to be constructed on Blue Nile Sudan, in Ethiopia, review of operation rules for existing reservoir would be required in order to facilitate the optimum operation of the combined system.

- The environmental capacity and proper water governance are the most difficult issues and most of the Nile basin countries are well behind on these regards.

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