WORKING PAPER 131

A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin

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FUTURE HARVEST
IWMI is a Future Harvest Center supported by the CGIAR

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IWMI receives its principal funding from 58 governments, private foundations and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR). Support is also given by the Governments of Ghana, Pakistan, South Africa, Sri Lanka and Thailand. The CGIAR Challenge Program on Water and Food (CPWF) supported the work reported here; the Cornell University (CU), USA, and the Omdurman Islamic University, UNESCO Chair in Water Resources (OIU, UNESCO-CWR), Sudan, have contributed to this paper.

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Awulachew, S. B.; McCartney, M.; Steenhuis, T. S; Ahmed, A. A. 2008. *A review of hydrology, sediment and water resource use in the Blue Nile Basin*. Colombo, Sri Lanka: International Water Management Institute. 87p. (IWMI Working Paper 131)

/ hydrology / sedimentation / river basins / water supply / water demand / climate / models / runoff / erosion / irrigation programs / reservoirs / Africa / Sudan / Ethiopia /

ISBN 978-92-9090-699-5

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Acknowledgement

This report is based on an output of the project, "Improved water and land management in the Ethiopian highlands and its impact on downstream stakeholders dependent on the Blue Nile", funded by the CGIAR Challenge Program on Water and Food (CPWF) and implemented by the International Water Management Institute (IWMI) in collaboration with the International Livestock Research Institute (ILRI), Cornell University (CU), Addis Ababa University (AAU), Bahir Dar University (BDU), Omdurman Islamic University-UNESCO Chair in Water Resources (OIU, UNESCO-CWR), Amhara Regional Agricultural Research Institute (ARARI) and the Forum for Social Studies (FSS) with further cooperation from the Ethiopian and Sudan institutions and the Nile Basin Initiative. We are very grateful to the CPWF and its staff members for providing us with the opportunity to do this work. We hope that the report and accompanying outputs will be useful to the CPWF and to others considering investment in water management for improved livelihood and environment in river basins in general and the Nile Basin in particular.

IWMI is also grateful to officials from the various institutions in Ethiopia and Sudan as well as the Nile Basin Initiative, particularly the Eastern Nile Technical Regional Organization. A number of officials from regional/provincial governments also took a lot of time to provide information and we are grateful to all of them.

With all this input, however, the authors remain responsible for the contents of this report.

Summary

This report presents a comprehensive literature review and broad-based analysis of the water resources of the Blue Nile (Abay) River. This work was undertaken as the initial phase in a study to evaluate approaches for improved land and water management in the Ethiopian highlands and assess the likely implications for downstream stakeholders in Sudan. Data and information have been compiled in relation to hydrology, sediment and water use in the basin. Section 1, *Introduction*, provides a context through the consideration of water resources both in Africa and the whole of the Nile Basin. Section 2, *Blue Nile Physiography*, presents an overview of the characteristics of the Blue Nile Basin, including a description of the meteorological monitoring network and the availability of historic data. It also reviews the geology, soil and land-use, and land-cover of the basin based on secondary sources. Section 3, *Hydrology of the Blue Nile*, describes the hydrology of the Blue Nile, including seasonal variation and trends over time. A summary of past hydrological modeling in the Nile and the Blue Nile is also presented. Section 4, *Soil Erosion and Sedimentation*, focuses on erosion and sediment transport and presents an overview of sediment in the major tributaries, including seasonal variations and trends over time. Section 5, *Water Resource Development*, reviews existing water resource development in both Ethiopia and Sudan and discusses the future potential with respect to major water uses (i.e., irrigation and hydropower). Section 6, *Discussion/ Recommendations*, provides a summary of the research methods and models to be used in the study. The reference materials collated and listed at the end of this report provide an important resource for water management and future research to be undertaken in the basin.

1. INTRODUCTION

The project "Improved water and land management in the Ethiopian highlands and its impact on downstream stakeholders dependent on the Blue Nile" is being undertaken as part of the CGIAR Challenge Program on Water and Food (CPWF). The aim of the project is to provide insight into the likely downstream impacts of upstream development and watershed management options. The project is being conducted through a collaboration of partners from global institutions, advanced universities from the north and institutions in both Ethiopia and Sudan, including IWMI, ILRI, Cornell University, Addis Ababa University, Omdurman Islamic University-UNESCO Chair in Water Resources, Bahir Dar University Forum for Social Studies and Amhara Regional Agricultural Research Institute. The aim of this report is to provide a context for the study and baseline information on the basin as well as a rationale and description of the methods to be used.

1.1. Cooperative Management of Transboundary Basins - Global Context

The world's 263 transboundary basins cover nearly half of the earth's surface (excluding Antarctica), produce around 60% of global freshwater flow and are home to approximately 40% of the world's human population. In the past, much of the political interest in transboundary basins has focused on their potential to increase international tension and conflict. However, it is increasingly recognized that transboundary rivers can serve as a focal point for cooperation and security between riparian states and act as an engine for shared economic growth and poverty alleviation. In fact, it is now widely recognized that the cooperative potential of transboundary basins is far greater than their potential to increase conflict. Nonetheless, achieving this cooperation requires overcoming tension between the water use desires of upstream and downstream riparians. One method by which this tension may be overcome is to move thinking, negotiations and actual practice beyond the zero-sum game of water allocation and towards the broader concept of sharing water benefits (Sadoff and Grey 2002). There are now numerous examples from around the world of the formation of transboundary institutions to facilitate benefit sharing between riparians. However, the institutional framework which best facilitates cooperation within any particular basin, depends on the specific hydrologic, economic and political nature of the basin as well as the goals and desires of the basin governments and their populations.

1.2. The State of Transboundary Basins in Africa and Their Potential

Africa is the world's second-largest and second most-populous continent, after Asia. At about 30,221,532 square kilometers (km^2), it covers 6.0% of the Earth's total surface area, and 20.4% of the total land area. With more than 900,000,000 people (as of 2005) in 61 territories, it accounts for about 14% of the world's human population. The continent is surrounded by the Mediterranean Sea to the north, the Suez Canal and the Red Sea to the northeast, the Indian Ocean to the southeast, and the Atlantic Ocean to the west. There are 46 countries including Madagascar, and 53 including all the island groups (Wikipedia 2007). In Africa, the potential for using benefit sharing in transboundary water management and development is tremendous. With the exception of island states, every African country has territory in at least one transboundary river basin. Transboundary basins cover 62% of Africa's total land area, and virtually every basin greater than 50,000 km^2 crosses at least one national boundary. Because of the transboundary nature of most of the continent's rivers, most African water management is, by definition, transboundary water management (Lautze and Giordano 2006).

The continent of Africa is rich in natural resources including water resources. Yet, the exploitation of water is shrouded in complex parameters ranging from boundaries demarcated by colonial powers in response to political, military and economic interests to a bewildering diversity of factors relating to unstable rainfall regimes, annual and seasonal flow variations and numerous basins and catchments. Despite the abundance, water resources, they are (like most other natural resources) not exploited to the full extent possible or properly developed, managed and utilized (UNECA 2000).

Nearly 80 major transboundary rivers/lake basins are located in Africa. Seventeen of these have catchment areas of more than 100,000 km^2 and some are shared by as many as ten countries. The entire surface area of some fourteen African countries falls within one or more transboundary river/lake basin (UNECA 2000) (Figure 1). The central rain forest belt, lying on either side of the equator, has high annual precipitation and is the source of some of the largest river systems in the world (e.g., the Congo, the Nile and the Zambezi). In contrast, some of the driest parts of the world (e.g., the Sahara and Kalahari deserts) are also found in Africa. Much of the continent faces the challenge of recurrent drought, severe flood and desertification, a challenge which is likely to be exacerbated by climate change.

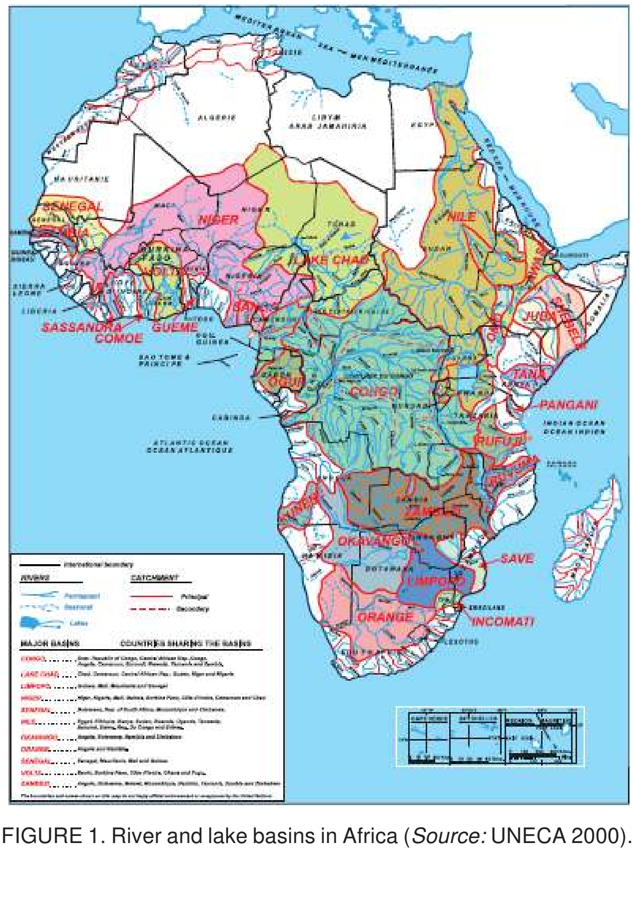


FIGURE 1. River and lake basins in Africa (*Source:* UNECA 2000).

Therefore, Africa needs to adopt the integrated water resources management process which requires all forms of water to be considered. Water can be roughly grouped into two categories: Blue water (i.e., the water resources contained in rivers, lakes and accessible groundwater), and green water (i.e., the rainwater stored in the soil and subsequently transpired by plants). The scarcities and shortages forecasted in many reports refer mainly to the blue water and do not account for the potential of green water use in agricultural production. The latter, if well utilized through proper watershed management, can make a great difference regarding the socioeconomic development in the upstream areas as well as in the downstream areas.

In most of sub-Saharan Africa, the great bulk of food production is not related to "blue" water use, but is, in fact, produced with "green" water in rainfed agriculture. As an example, in Ethiopia, more than 90% of the food is produced with "green" water in rainfed agriculture. Still, most research, like in all other African countries, is related primarily to blue water usage. This is based partly on an old paradigm promoted during the green revolution: By breeding better crops on irrigated land (or without regard for water needs) the world's food problems can be solved. Neither the breeding of better crops in irrigated land nor the management of rainwater for agriculture is done effectively in Africa. Despite the huge success of the green revolution (especially in Asia), the African continent remains behind the rest of the world in crop production and, consequently, cannot meet the basic food needs of its population. The green revolution in Asia was primarily the result of:

i) improved soil fertility management,

ii) the introduction of high yielding varieties,

iii) better water management, including irrigation development with surface water, groundwater and rainwater, and

iv) favorable economic conditions arising from the high market price of agricultural produce.

Investment in these areas has been very limited in Africa and the continent has largely been bypassed by the green revolution.

Solutions combining various measures are needed and, in addition to the development of the blue water resources, emphasis needs to be placed on increasing the productivity of the green water. The Comprehensive Assessment of Water Management in Agriculture discusses details of the whole continuum of management of water for agriculture including upgrading rainfed systems (Molden 2007). Unlike blue water, where it is not uncommon for one engineering solution to solve a number of problems, green water optimization is complicated by many factors, including societal needs, climate, and environmental conditions, all of which vary greatly across the African continent. Hence, each region has its unique solution for optimizing water use. For example, in Ethiopia, where most of the agricultural production is dependent on rainfall, one of the most obvious solutions is to store more rain in the soil by increasing the infiltration capacity. On the other hand, little attention is given to rainfed agriculture in research studies.

1.3. The Nile River Basin

The Nile River, at 6,825 kilometers (km), is the longest river in the world (http://www.britannica.com). Ahmed and ElDaw (2004) reported that the length of the Nile River from its remotest point is 6,671 km. It comprises two major tributaries, the White Nile and the Blue Nile (known as the Abay in Ethiopia). The White Nile rises in the Great Lakes region of Central Africa, with the most distant source in southern Rwanda and flows north from there through Tanzania, Lake Victoria, Uganda and southern Sudan. The Blue Nile starts at Lake Tana in Ethiopia, and flows into Sudan from the southeast. The two rivers meet near the Sudanese capital, Khartoum, and flow north through Sudan and Egypt to drain into the Mediterannean Sea. The drainage area is officially described by the Nile Basin Initiative (NBI 2007) as 3 million km^2, but the values given by various authors vary: 3.255 million km^2 (Revenga et al. 1998), 3.3 million km^2 (CPWF 2007), 3.1 million km^2 (FAO 2007), etc. The ten countries that share the Nile River Basin are: Burundi, Democratic Republic of Congo (DRC), Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda. The Nile River Basin is home to approximately 180 million people, while over 350 million (based on World Bank 2006) live within the 10 riparian states. According to the World Bank (2006) data, the Nile region is characterized by high population growth and considerable development challenges. Five of the ten countries are among the poorest in the world with gross national per capita incomes of $90 (Burundi), $110 (DRC and Ethiopia), $190 (Eritrea) and $210 (Rwanda). Life expectancy varies from 42 in Ethiopia to 70 in Egypt. Child mortality rate per thousand varies from 210 in DRC to 36 in Egypt. Most of the population in the Nile Basin live in rural areas and are dependent on agriculture (Table 1).

TABLE 1. Proportion of total agricultural population in East Africa, including forestry and fisheries (analysis based on FAO statistical yearbook 2004 (FAO 2007). Data includes population).

	Countries	Year				
		1979-1981	1989-1991	1999-2001	2003	2004
1	Burundi	93	92	90	90	90
2	DRC	72	68	63	62	61
3	Egypt	60	44	37	35	34
4	Eritrea	N/A	N/A	78	77	76
5	Ethiopia	89	86	82	81	81
6	Kenya	82	80	75	74	74
7	Madagascar	82	78	74	73	72
8	Rwanda	93	92	91	90	90
9	Sudan	72	69	61	58	57
10	Tanzania	84	82	78	77	76
11	Uganda	86	84	79	77	77

Figures 2a and 2b show various characteristics of the Nile Basin according to watersheds of Africa (IUCN 2007). Table 2 provides summary statistics of the key tributaries.

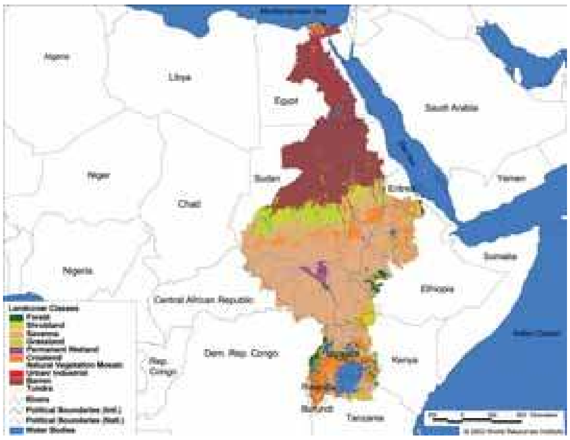


FIGURE 2a. Land Cover.

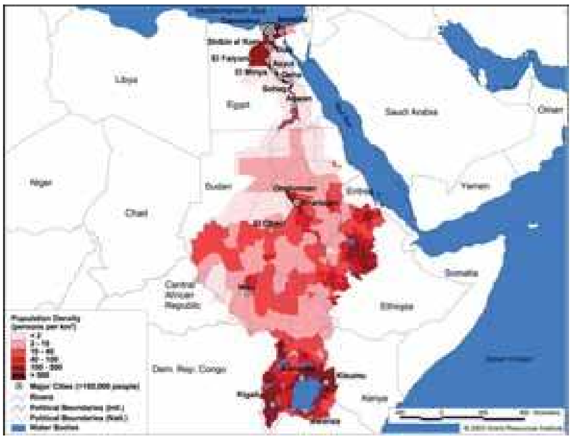


FIGURE 2b. Population.

TABLE 2. Nile Basin: Areas and flow of major tributaries. *Sources:* Area from Mohamed et al. (2005); Flows from Sutcliffe and Parks (1999).

No.	Catchment	Outlet location	Area (1,000 km^2)	Mean annual flow (km^{3}yr^{-1*})
1	Nile	Mediterranean	3,310	
2	Nile	Aswan	3,060	84.1
3	Atbara	Atbara	180	11.1
4	Blue Nile	Khartoum	330	48.3
5	White Nile	Khartoum	1,730	26.0
6	White Nile	Malakal	1,480	29.6

[*] Naturalized flows for the period 1910 to 1995

The average annual flow of the White Nile at Khartoum is approximately 26 cubic kilometers (km^3). The remaining flow of 58.1 km^3 comes from the Blue Nile and the Tekezze-Atbara. The seasonal flow pattern exhibits the combined characteristics of these two main tributaries, with the seasonal pattern of the Blue Nile superimposed on the regular pattern of the White Nile. The total annual flow at the border with Egypt has historically been taken (before any significant abstraction) as 84 km^3 (1905-1959). However, there are considerable year-on-year variations as well as periodic variations (Figure 3) (Ahmed 2006; Hydrosult Inc et al. 2006a).

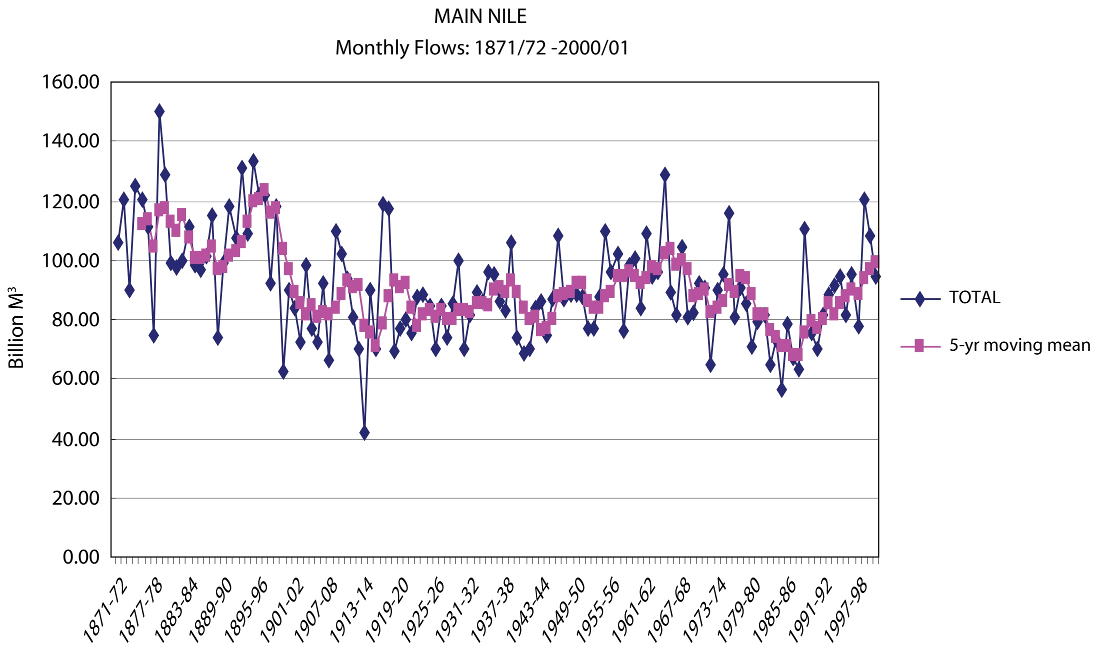


FIGURE 3. Main Nile: Monthly discharges and five-year moving mean 1871/72-2000/01.

The years 1871 to 1896 was a period of high flows as a consequence of high lake levels across East Africa. Between 1901 and 1975 annual discharges averaged around 87 km^3. The decade from 1976 to 1987 saw a series of very low flows with average annual flow only about 76 km^3. Since then flows have increased again.

1.4. The Project Rationale

The need for integrated water resources management to alleviate poverty and food insecurity in semi-arid Africa cannot be over-emphasized. In the Nile Basin, water from the Ethiopian highlands, particularly from the Blue Nile, has, historically, mainly benefited downstream people in Sudan and Egypt in different ways: agriculture, livestock, industry and electrical power. However, such benefits are now affected and continue to be affected due to dramatically changing land, water and livestock management practices upstream. High population pressure, lack of alternative livelihood opportunities and the slow pace of rural development are inducing deforestation, overgrazing, land degradation and declining agricultural productivity. Poor water and land management in upstream areas reduces both potential runoff yields and the quality of water flowing downstream. The result is a vicious cycle of poverty and food insecurity for over 14 million poverty-stricken people in the uplands, and for millions of downstream users. It is widely recognized that improved water management in the Abay Catchment is key to improving both upstream and downstream livelihoods. Better water management will help increase water availability and alleviate the impacts of natural catastrophes such as droughts and reduce conflicts among stakeholders dependent on the Nile.

Currently, the Abay is one of the least planned and managed sub-basins of the Nile. About two-thirds of the area of this densely populated basin fall in the highlands and, hence, receive fairly high levels of rainfall of 800 to 2,200 mm yr^{-1}. However, it is erratic in terms of both spatial and temporal distribution, with dry spells that significantly reduce crop yields and sometimes lead to total crop failure. The impacts of droughts on the people and their livestock in the area can be catastrophic. The population located in the downstream part of the Blue Nile, is entirely dependent on the river water for supplementary irrigation. Canal and reservoir siltation is a major problem exacerbating socioeconomic burdens, besides the seasonality of the river flow, on poor riparian farmers. Solutions lie in improving agricultural practices and conserving water at all levels by all stakeholders, both within Ethiopia and amongst downstream communities. Though well known in principle, the technologies required for overcoming the poor and extreme distribution of water resources are not applied because of poor adaptation to the local conditions, unavailability of capital, institutional constraints and inadequate scientific knowledge. The underlying premise of this study is that with increased scientific knowledge of the hydrological, hydraulic, watershed, and institutional processes of the Blue Nile, constraints to up-scaling management practices and promising technologies within the catchment can be overcome, resulting in significant positive benefits for both upstream and downstream communities. The specific objectives of the project are to:

1. Identify major water, land and livestock management constraints and opportunities and assess the upstream and downstream impacts of current and future water, land and livestock management interventions within the catchment.
2. Adapt and apply existing hydrological, watershed, and economic models to estimate the likely economic implications of interventions both basin-wide and locally, in selected communities, including impacts on poverty.
3. Create an overview of 'best-bet' management practices and interventions, for improved land and water management and evaluate the hydrological and socioeconomic conditions, including institutional arrangements, necessary for up-scaling them.

Furthermore, such studies help the decision-makers to adapt their water and land management policies by making use of the new management interventions in the upstream watersheds, upstream-downstream water availability, and demand and supply.

1.5. Specific Project Components of Modeling Sediment and Water Supply, and Demand and Supply

In the past, a great deal of research has been conducted into water and land management options in Ethiopia. However, this project is unique in its sharp focus on recognizing and then structuring interventions to account for upstream/downstream impacts. The project takes a holistic basin-wide view and will investigate those interventions that alleviate poverty and reduce environmental degradation, while at the same time maximizing benefits and minimizing harm to downstream stakeholders. The importance of these upstream-downstream linkages are clear both within Ethiopia, where the fragility of the landscape and the vulnerability of the population must be considered downstream of any intervention, and across borders in Sudan and Egypt, where impacts may arise as a result of changing land and water management practices upstream.

These linkages are likely to be seen most directly through changes in river flows, sedimentation and water quality. The project, therefore, seeks interventions that either minimize changes in river flows or makes changes in river flows that result in positive benefits downstream (e.g., moderating floods and droughts and ensuring adequate environmental flows). With regard to sediment, understanding the causes of erosion, sediment transport and its dynamic as well as changes in sedimentation and water quality are very important. The project seeks poverty alleviation through land and water management interventions that will not degrade downstream water quality, but will ideally enhance it (e.g., through erosion control, restoration of wetlands or effluent control).

To address these issues, two key components of the study are watershed modeling and water allocation modeling. These components comprise:

Development of a Watershed Management Model which considers generation of flows, nutrients, sediments and bio-economic factors. The objectives of the model are to:

- predict the effect of management decisions and up-scaling interventions on water, sediment and nutrient yields; and
- assess the impact of upstream water management scenarios on downstream users, especially reservoir sedimentation, based on sediment input and sediment trap efficiency.

Development of a Water Demand and Supply Model to consider the estimation of water for major production activities (both existing and planned) and assess the potential for meeting these requirements. The objectives of the model are to:

- provide insight on water availability and estimation of water for major production activities; and
- assess impacts of upstream water resource development on water availability and hydrology downstream.

1.6 Overview of this Report

As a collation of baseline information for the study described above, this report provides a detailed description of the Blue Nile River. As such it:

- identifies the data and information systems that can be used for detailed analyses;
- provides an overview of the climate and hydrology of the system, erosion, sediment transport and sedimentation;

- provides an overview of current and possible future water resource developments in the Basin; and
- reviews possible models and how they might be configured for the study.

2. BLUE NILE PHYSIOGRAPHY

The Blue Nile Basin covers an area of 311,548 km^2 (Hydrosult Inc et al. 2006b). It provides 62% of the flow reaching Aswan (World Bank 2006). The river and its tributaries drain a large proportion of the central, western and south-western highlands of Ethiopia before dropping to the plains of Sudan. The confluence of the Blue Nile and the White Nile is at Khartoum. The basin is characterized by a highly rugged topography and considerable variation of altitude ranging from about 350 meters (m) at Khartoum to over 4,250 meters above sea level (masl) in the Ethiopian highlands (Figure 4a). The Dinder and Rahad rise to the west of Lake Tana and flow westwards across the border joining the Blue Nile below Sennar (Figure 4b).

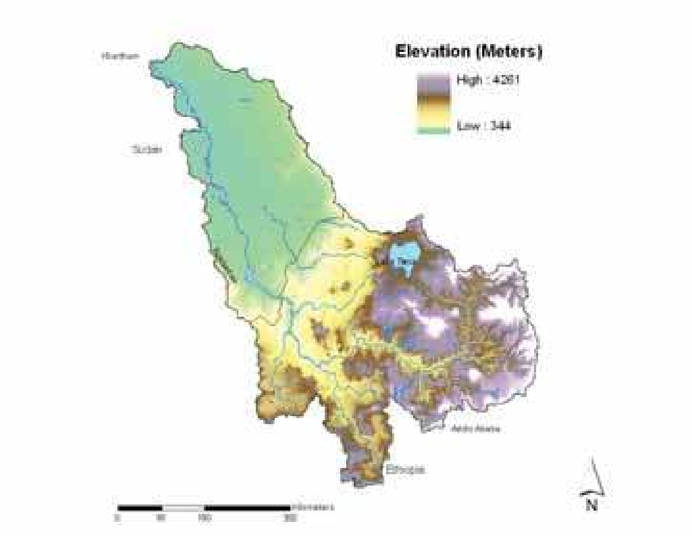


FIGURE 4a. Map of the Blue Nile showing elevation, main tributaries and key geographic features (*Source:* IWMI 2007).

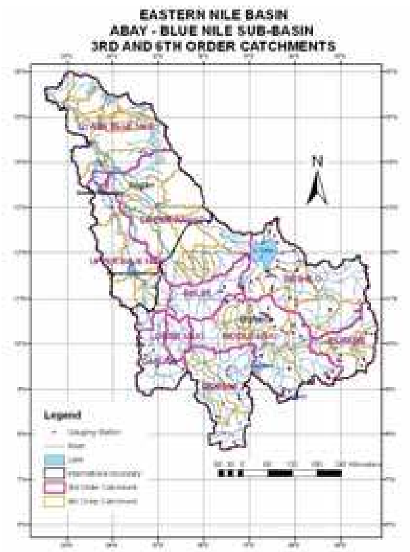


FIGURE 4b. Abay-Blue Nile Sub-basin: 3rd and 6th order watersheds(*Source:* Hydrosult Inc et al. 2006b).

The Abay's source is Gish Abay in West Gojam. From here it flows northward as the Gilgel Abay[1] into Lake Tana (Figure 5). Lake Tana is the biggest lake in Ethiopia and is some 73 km long and 68 km wide. It is located at 1,786 masl and has a surface area of 3,042 km^2, accounting for 50% of the total inland water of Ethiopia (Hydrosult Inc et al. 2006b). Little of the 13,750 km^2 catchment draining into the lake is above 2,400 masl, though it rises to approximately 4,000 masl to the northeast, in the Simien Mountains. There are approximately 40 rivers draining into the lake, many of which have catchment areas of less than 1,000 km^2 and are ephemeral (Kebede et al. 2006). In addition to the Gilgel Abay, three other major rivers, Gumera, Ribb and Megech flow into the lake. The lake stores 29.175 km^3 of water which fluctuates seasonally between 1,785 and 1,787 masl. The lake is shallow and has a mean depth of 9.53 m, while the deepest part is 14 m.

[1] "Gilgel" in Amharic means "baby"

(a) (b)

FIGURE 5(a). Lake Tana in the Ethiopian Highlands (*photo credit:* Matthew McCartney); (b) satellite image of the Lake.

The Abay leaves the lake close to the city of Bahar Dar at the southeastern corner of the lake and cuts a deep gorge first south then westwards, through a series of cataracts. Approximately 40 km downstream it drops 50 m over the Tiss Issat Falls (Figure 6) into the Blue Nile gorge. The river then follows a deep and circuitous, 900 km, course, through the Ethiopian Highlands. It first flows southeast, before looping back on itself, flowing west and then turning northwest and traversing through Sudan. In the highlands, the basin is composed mainly of volcanic and Pre-Cambrian basement rocks with small areas of sedimentary rocks. The catchment is cut by deep ravines in which the major tributaries flow. The valley of the Blue Nile itself is 1,300 m deep in places (Figure 7). The whole area is intersected by streams, many of which are perennial though highly seasonal in their flow. The primary tributaries of the Blue Nile in Ethiopia are the Beshio, Jema, Muger, Guder, Finchaa, Anger, Didessa and Dabus on the left bank, and Beles, and smaller tributaries Chemoga, Timochia and Bir on the right bank.

FIGURE 6. Tiss Issat Falls.

FIGURE 7. Blue Nile Gorge (*photo credit:* Matthew McCartney).

The Blue Nile enters Sudan at an altitude of 490 meters amsl and just before crossing the frontier, the river enters the clay plain, through which it flows over a distance of about 630 km to Khartoum. At Khartoum the Blue Nile joins the White Nile to form the main stem of the Nile River. Below the Damzain rapids at Rosieres, where the main reservoir storing Blue Nile waters for irrigation in Sudan was built (Figure 8), the character of the Blue Nile changes in response to the change of gradient. Here the river is only just below the level of the surrounding plain and some areas are flooded during the rainy season. The average slope of the river from the Ethiopian frontier to Khartoum is only about 15 cm km^{-1}. Within Sudan, the Blue Nile receives water from two major tributaries draining from the north, the Dinder and the Rahad (Table 2). These drain both countries and join the main Blue Nile upstream of Khartoum. Both are highly seasonal, with no flow in the dry season (January to May). They are nearly equally long, about 750 to 800 km. The Blue Nile joins the White Nile at an elevation of approximately 400 masl, but still 2,800 km upstream of its Mediterranean delta. The total area of the Blue Nile Basin at this point is 311,548 km^2.

Table 3 presents the area and summary statistics for each of the major sub-basins in the Blue Nile Basin.

TABLE 3. Summary statistics for the major sub-basins of the Blue Nile.

No.	Sub-basin	Catchment area (km^2)	Mean annual rainfall (mm)	Mean annual potential evapotranspiration (mm)	Mean annual runoff (mm)	Mean annual flow (Mm^3)	Coefficient of runoff
				Ethiopia			
1	Guder	7,011	910	1,307	312	2,187	0.34
2	Dabus	21,030	2,276	1,112	297	6,246	0.13
3	Finchaa	4,089	1,766	1,290	438	1,719	0.25
4	South Gojam	16,762	1,633	1,183	299	5,012	0.18
5	Anger	7,901	1,813	1,318	298	2,355	0.16
6	Beles	14,200	1,655	1,274	306	4,345	0.18
7	Didessa	19,630	1,816	1,308	289	5,673	0.16
8	Muger	8,188	1,347	1,210	298	2,440	0.22
9	North Gojam	14,389	1,336	1,242	305	4,389	0.23
10	Jemma	15,782	1,105	1,059	304	4,798	0.28
11	Lake Tana	15,054	1,313	1,136	253	3,809	0.19
12	Welaka	6,415	1,072	1,263	323	2,072	0.30
13	Beshilo	13,242	982	1,140	296	3,920	0.30
14	Wombera	12,957	1,660	N/A	299	3,874	0.18
15	Dinder	14,891*	N/A	N/A	188	2,797+	N/A
16	Rahad	8,269*	N/A	N/A	133	1,102+	N/A
				Sudan			
1	Upper Blue Nile	33,804	674	1,480	135	4,563	0.20
2	Dinder-Rahad	38,851*	620	1,570	124	4,817	0.20
4	Lower Blue Nile	5,530	430	1,960	68.8	380	0.16

Source: For Ethiopia, data are taken from MoWR (1998) and Tesfahun et al. (2006). For Sudan, * data are taken from Hydrosult Inc et al. (2006b)[2]

2.1. Climate

2.1.1. Rainfall and its Distribution

Rainfall varies significantly with altitude and is considerably greater in the Ethiopian highlands than on the Plains of Sudan. Rainfall ranges from nearly 2,000 mm/yr in the Ethiopian Highlands to less than 200 mm/yr at the junction with the White Nile. Within Sudan, the average annual rainfall over much of the basin is less than 500 mm. In Ethiopia, it increases from about 1,000 mm near the border of Sudan to between 1,400 and 1,800 mm over parts of the upper basin, in particular, in the loop of the Blue Nile south of Lake Tana. Rainfall exceeds 2,000 mm in parts of the Didessa and Beles catchments (Figure 8).

Both the temporal and spatial distribution of rainfall is governed, to a large extent, by the movement of air masses associated with the Inter-Tropical Convergence Zone (ITCZ). During the winter dry season (known in Ethiopia as *Bega*) the ITCZ lies south of Ethiopia and the Blue Nile region is affected by a dry northeast continental air-mass controlled by a large Egyptian zone of high pressure. This cool airstream from the desert produces the dry season. From March, the ITCZ returns bringing rain particularly to the southern and southwestern parts of the Basin. This short period of rain is known in Ethiopia as the *Belg* or “small rains”. In May, the Egyptian high pressure

[2] Note here that there are significant variations in terms of area of the Blue Nile Basin, based on previous discussions. The overall estimated area is at 311,548 km^2. While the defined tributaries account to a total of 277,995 km^2, the remaining balance is probably attributed to the non-major rivers and the directly draining catchment area into the river. Also note that, some reports show the total area of the Blue Nile as being 331,000 km^2. This will be clarified further in the future.

strengthens and checks the northward movement of the ITCZ producing a short intermission before the main wet season (known in Ethiopia as the *Kremt*). Around June, the ITCZ moves further north and the southwest airstream extends over the entire Ethiopian highlands to produce the main rainy season. This is also the main rainy season in Sudan, though being further north and at lower altitude, the period of rainfall is foreshortened and totals are considerably less than in Ethiopia (Table 4). The summer months account for a large proportion of mean annual rainfall; roughly 70% occurs between June and September and this proportion generally increases with latitude, ranging from 61% at Gore in the southwest to 73% at Debre Marcos, 78% at Gonder, 87% at Rosieres and 93% at Khartoum (Figure 9; Table 5).

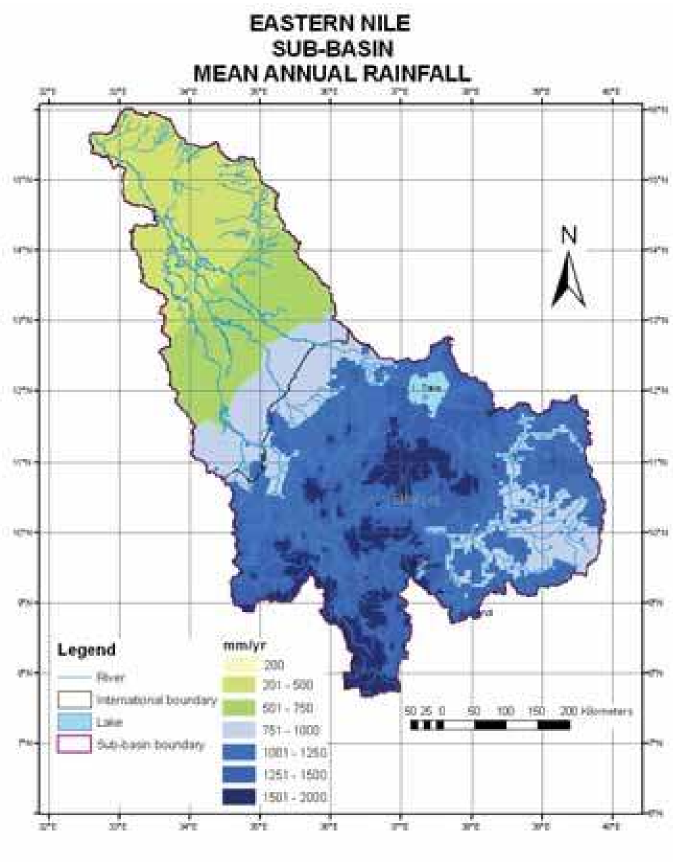


FIGURE 8. Mean annual rainfall across the Blue Nile Basin (mm yr^{-1}) (*Source:* Hydrosult Inc et al. 2006b).

TABLE 4. Summary statistics for representative climate stations, located in, or close to, the Blue Nile Basin.

Climate Station	Location Latitude	Location Longitude	Elevation (masl)	Mean annual rainfall (mm)	Range in Mean Monthly temperature (°C)	Potential Evapotrans-piration (mm)
Ethiopia						
Gonder	12.53	37.43	1,966	1,095	17.9 – 22.7	1,524
Bahar Dar	11.60	37.40	1,805	1,453	18.1 – 22.4	1,388
Debre Marcos	10.35	37.72	2,440	1,320	14.2 – 18.6	1,172
Debre Tabor	11.88	38.03	2,410	1,651	15.0 – 18.7	1,363
Addis Ababa	8.98	38.80	2,324	1,191	15.5 – 18.2	1,234
Sibu Sire	9.02	36.87	1,750	1,370	18.2 – 21.6	N/A
Jimma	7.67	36.83	1,577	1,477	18.0 – 20.8	1,301
Gore	8.17	35.55	1,974	2,176	16.1 – 20.3	1,263
Gambela	8.25	34.58	480	1,197	25.4 – 30.2	1,658
Assossa	10.07	34.52	1,750	1,116	19.4 – 24.4	1,463
Sudan						
Hawata	13.40	34.60	440	566	N/A	N/A
Rosieres	11.83	34.37	465	655	26.2 – 32.2	N/A
Sennar	13.55	33.62	418	434	20.5 – 28.5	2,149
Wad Medani	14.40	33.48	408	305	23.5 – 32.8	2,534
Khartoum	15.60	32.55	380	140	22.8 – 34.5	2,625
Rahad	12.70	30.63	495	428	22.5 – 30.9	N/A

Source: FAO-CLIM2 Worldwide agroclimatic database
Note: N/A = Not available

TABLE 5. Mean monthly rainfall (mm) for representative climate stations located in, or close to, the Blue Nile Basin.

Climate station	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ethiopia													
Gonder	5	4	19	34	87	151	311	279	116	56	24	9	1,095
Bahar Dar	3	2	8	22	83	181	444	395	196	92	23	4	1,453
Debre Marcos	12	22	49	61	96	155	301	300	204	81	24	15	1,320
Debre Tabor	6	11	42	46	93	180	501	476	193	66	21	16	1,651
Addis Ababa	19	50	71	90	95	118	250	265	169	41	9	14	1,191
Sibu Sire	16	24	50	85	150	220	271	245	179	74	42	14	1,370
Jimma	30	52	95	128	166	209	213	210	183	93	66	32	1,477
Gore	39	46	98	119	234	327	336	335	337	166	102	37	2,176
Gambela	5	8	27	56	156	150	239	228	155	113	48	12	1,197
Assossa	0	0	31	32	118	189	207	208	207	103	21	0	1,116
Sudan													
Hawata	0	0	0	2	12	97	142	210	82	20	1	0	566
Rosieres	0	0	1	12	36	119	157	175	121	33	1	0	655
Sennar	0	0	0	3	14	60	113	143	75	25	1	0	434
Wad Medani	0	0	0	1	13	28	88	111	46	16	2	0	305
Khartoum	0	0	0	0	4	7	43	63	17	5	1	0	140
Rahad	0	0	0	2	25	37	138	130	71	24	1	0	428

Source: FAO-CLIM2 Worldwide agroclimatic database

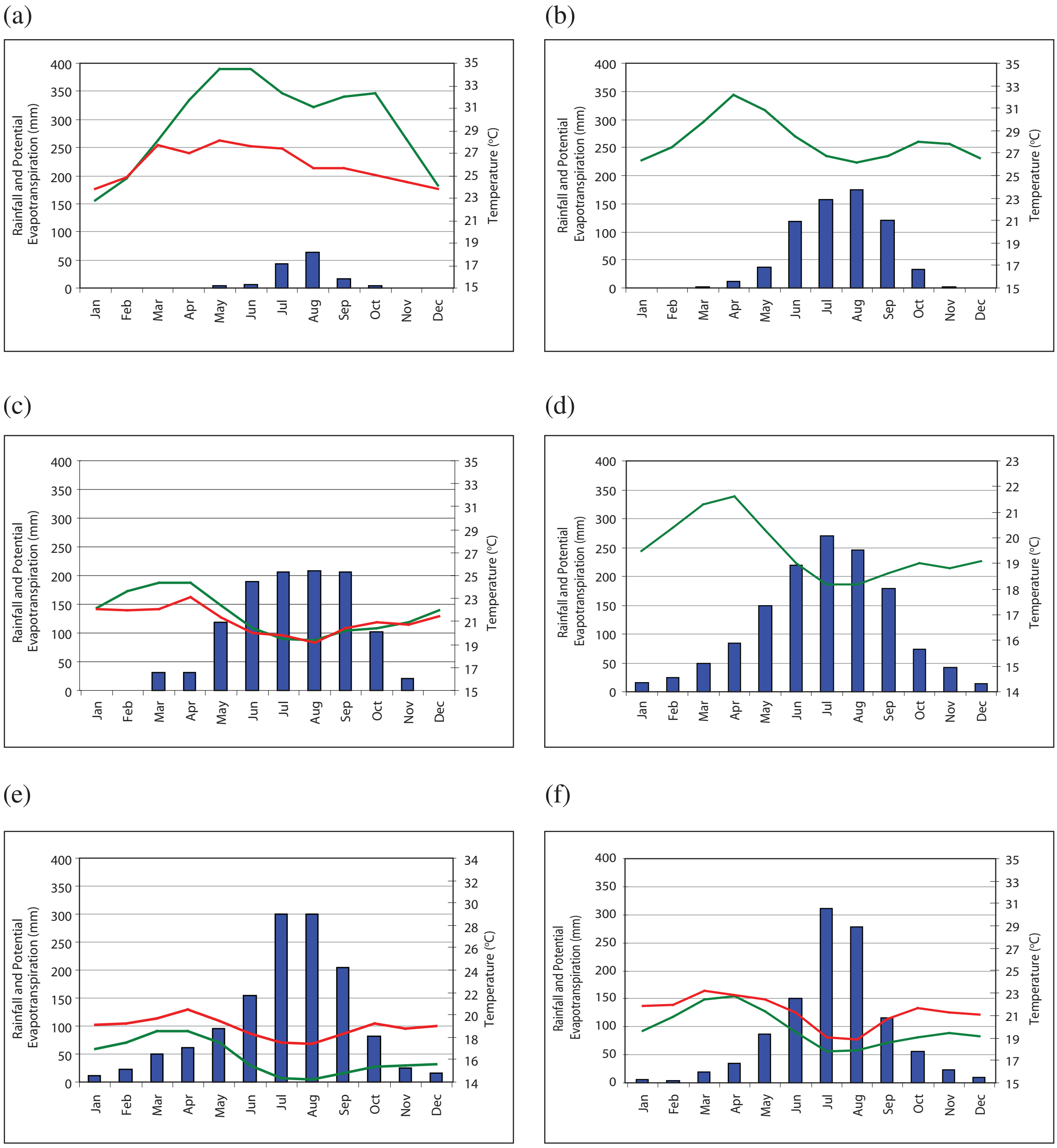


FIGURE 9. Annual variation in temperature (blue bars), potential evapotranspiration (red line) and rainfall (green line) at six representative sites in the Blue Nile: a) Khartoum, b) Rosieres, c) Assossa, d) Sibu Sire, e) Debre Marcos, and f) Gonder.

2.1.2. Temperature

The spatial distribution of temperature values is strongly related to altitude (Figure 10). The highest mean annual temperatures occur in the northeastern clay plains of Sudan. In Sudan, daily minimum and maximum temperatures in January are 14°C and 33°C, and those in May are 24°C and 44°C, respectively. The area located in the highlands of Ethiopia is characterized by lower minimum mean monthly temperatures that range between 3°C and 21°C, and occur between December and February.

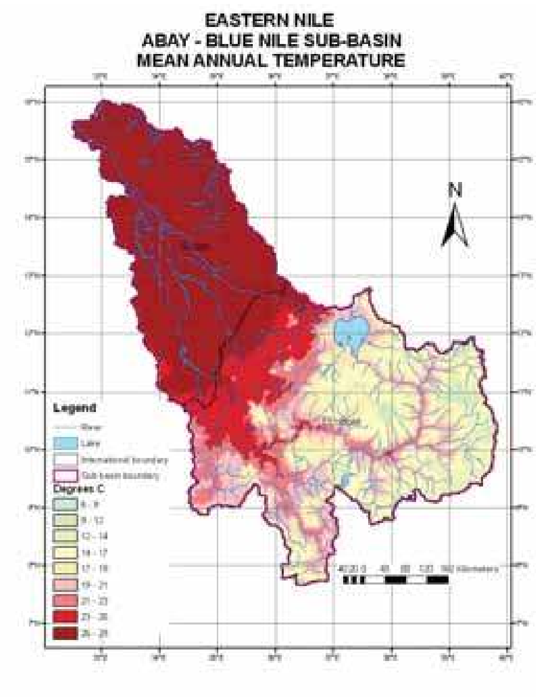


FIGURE 10. Mean annual temperature (°C) in the Blue Nile Basin (*Source:* Hydrosult Inc et al. 2006b).

2.1.3. Evapotranspiration

Similar to rainfall and temperature, potential evapotranspiration also varies considerably across the basin and is highly correlated with altitude (Figure 11; Table 6). Throughout Sudan, values (computed using the Penman-Monteith method) generally exceed 2,200 mm per year and even in the rainy season (July to October) rainfall rarely exceeds 50% of potential evapotranspiration. Consequently, irrigation is essential for the growth of crops. In the highlands of Ethiopia, potential evapotranspiration ranges from approximately 1,300 to 1,700 mm per year and in many places is less than rainfall in the rainy season. Consequently, rainfed cultivation, producing a single crop in the rainy season, is possible, though at a risk in low rainfall years.

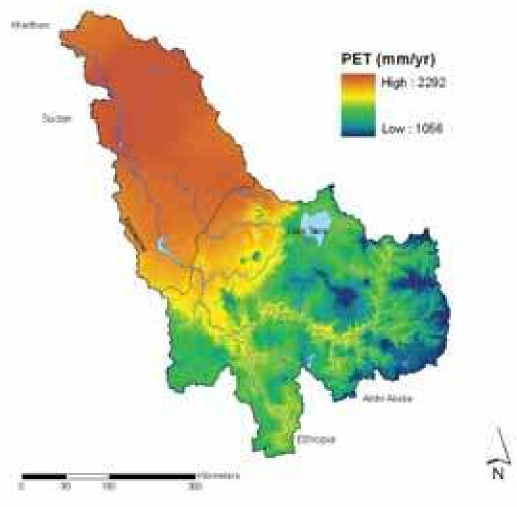


FIGURE 11. Mean annual potential evapotranspiration across the Blue Nile Basin (*Source*: IWMI 2007)

TABLE 6. Mean monthly potential evapotranspiration (mm) for representative climate stations located in, or close to, the Blue Nile Basin.

Climate station	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ethiopia													
Gonder	136	140	164	156	149	126	81	78	114	133	126	121	1,524
Bahar Dar	115	118	152	156	136	108	81	81	105	118	111	109	1,388
Debre Marcos	102	104	115	129	109	87	71	68	87	105	96	99	1,172
Debre Tabor	118	123	152	147	133	108	78	74	99	118	108	105	1,363
Addis Ababa	105	104	124	117	115	93	78	81	90	115	108	105	1,234
Sibu Sire	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Jimma	112	106	140	126	118	99	87	90	99	115	105	105	1,301
Gore	118	118	136	126	102	87	81	78	90	115	105	109	1,263
Gambela	159	154	164	165	140	117	115	102	123	140	135	146	1,658
Assossa	143	140	143	162	127	99	96	84	108	118	114	130	1,463
Sudan													
Hawata	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rosieres	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sennar	171	171	217	210	229	180	158	152	162	158	174	167	2,149
Wad Medani	192	204	245	240	264	258	214	177	180	183	189	189	2,535
Khartoum	177	196	254	240	264	252	248	214	213	213	202	189	2,625
Rahad	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Source: FAO-CLIM2 Worldwide agroclimatic database
Note: N/A = Not available

A complete list of climatic measuring stations in Ethiopia and Sudan for the Blue Nile Basin is provided in Appendix 1.

2.2. Geology[3]

The geology of the Blue Nile Basin (Figure 12) can be briefly summarized as:

- the highlands of the basin are composed of basic rocks, mainly basalts;
- the Ethiopian lowlands are mainly composed of Basement Complex rocks as well as metamorphic rocks, such as gneisses and marble. Where the Abay has cut through the basalts there are restricted areas of limestones and then sandstones before the Basement Complex is reached; and
- the main part of the lowlands of Sudan is underlain by deep unconsolidated colluvial sediments of tertiary and quaternary age. To the north are older Basement Complex rocks and the Nubian Sandstones. The Nubian Sandstones are located in the northwest corner, overlying the Basement Complex rocks and comprise mainly sandstones, siltstones and conglomerates.

2.3. Soils

The Vertisol–Nitisol boundary runs almost along the international boundary. Nitisols (24%) dominate the western Ethiopian Highlands whilst shallower and more infertile Leptosols (19%) occupy the eastern Ethiopian Highlands. On the flat plateaus in the Ethiopian Highlands are extensive areas of Vertisols. On the deep soils in the high rainfall areas around Lake Tana there are extensive areas of Luvisols. Vertisols (29%) dominate the unconsolidated sediments of the Sudan plains (see Figure 13) (Hydrosult Inc et al. 2006b).

[3]Note that the summary of geology, soils, and land cover and vegetation is extracted from the Hydrosult Inc et al. (2006b) document.

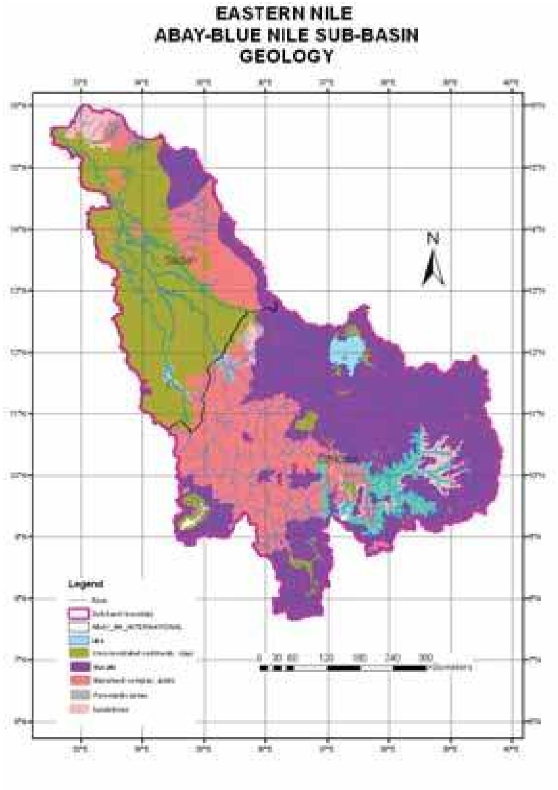


FIGURE 12. Geology of the Blue Nile Basin.

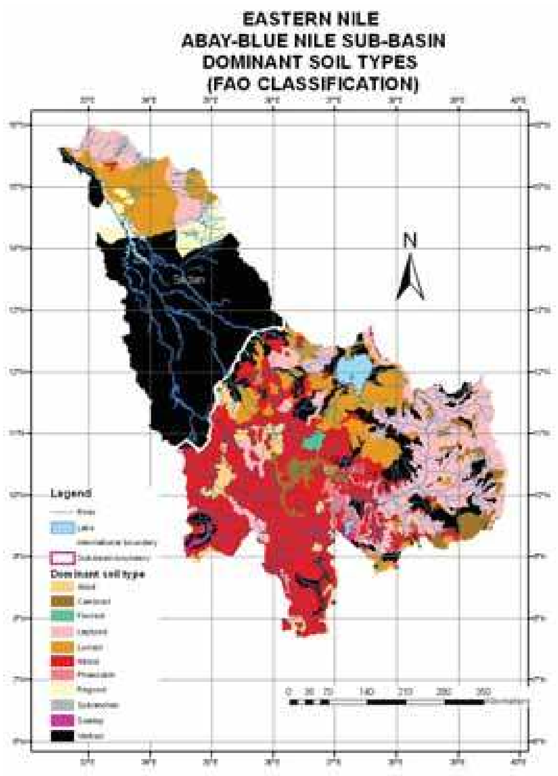


FIGURE 13. Dominant soil types in the Blue Nile Basin (*Source:* FAO Classification).

2.4. Land Cover and Vegetation

Table 7 and Figure 14 present the land cover of the Blue Nile. In the far north between the 75 mm and about the 250 mm isohyets "Semi-desert Scrub" is the most prevalent vegetation type, comprising a varying mixture of grass and herbs, with a variable scattering of shrubs up to 4 m high, interspersed with bare earth. Grass is mainly an annual plant in Sudan. Heavy grazing and low rainfall ensures that there is insufficient dry matter for annual fires. In years of low rainfall and heavy grazing there can be an almost complete failure of annual plant growth.

South-eastwards, from the 250 mm to the 360 mm isohyet, the vegetation type becomes "Semi-desert Grassland". Much of this vegetation is now covered by the Gezira and Managil irrigation schemes (see below). On the heavy alkaline clay soils the natural vegetation is grassland without trees or shrubs. Between the 360 and 570 mm isohyets on the heavy clays grassland merges into *A. mellifera* thornland. Above 570 mm to the border with Ethiopia there is increasing dominance of *A. seyal* in association with *Balanites aegyptiaca*. *A. senegal* is retained for gum arabic harvesting whilst *A. seyal* is used for charcoal production. *B. aegyptiaca* becomes increasingly prevalent because it is fire resistant.

Woodlands and shrublands cover some 28% and grasslands 25% of the basin. Sedentary rainfed cropping covers nearly 26% of the area mainly located in the Ethiopian Highlands. Semi-mechanized farms cover 10% and the irrigated schemes 2.6% of the basin. Much of the major Gezira and all of Managil schemes, although irrigated with water from the Blue Nile, lie in the White Nile Basin.

TABLE 7. Dominant land cover in the Blue Nile Basin (*Source:* Hydrosult Inc et al. 2006b).

Land cover type	Area (ha)	Total (%)
Rainfed crops: sedentary	8,037,337	25.8
Grassland	7,777,274	25.0
Woodland	5,225,555	16.8
Shrubland	3,671,919	11.8
Semi-mechanized farms	3,123,087	10.0
Irrigated crops	815,480	2.6
Rock	732,392	2.4
High forest	429,777	1.4
Water	420,103	1.3
Rainfed crops: shifting	340,930	1.1
Plantation	211,977	0.7
Sand	128,804	0.4
Seasonal swamp	94,518	0.3
Permanent swamp	51,831	0.2
Urban	65,136	0.2
Afro-alpine	28,680	0.1
Sub-basin	31,154,800	

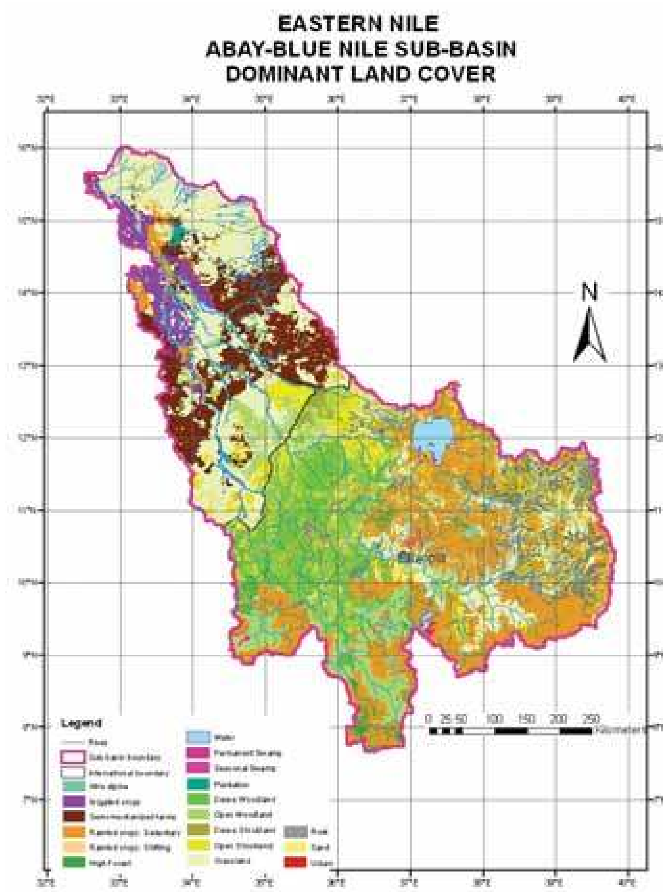


FIGURE 14. Dominant land cover of the Blue Nile Basin (*Source*: Hydrosult Inc et al. 2006b).

3. HYDROLOGY OF THE BLUE NILE

3.1. Flow

Throughout the Blue Nile Basin, river flow data are generally limited because of the remoteness of many of the catchments and the lack of economic resources and infrastructure to build and maintain monitoring sites. In Ethiopia, although there are over 100 flow gauging stations in the basin, most of these are located on relatively small tributaries and/or near the headwaters of the main rivers. Very few gauged catchments are over 1,000 km^2 and very few gauging stations are located on the main stem of the river or on the major tributaries close to their confluence with the Blue Nile (Figure 15). Table 8 lists some of the most important flow gauging stations, with reasonably long records, in the Blue Nile Basin. A full list of measuring stations is provided in Appendix 2.

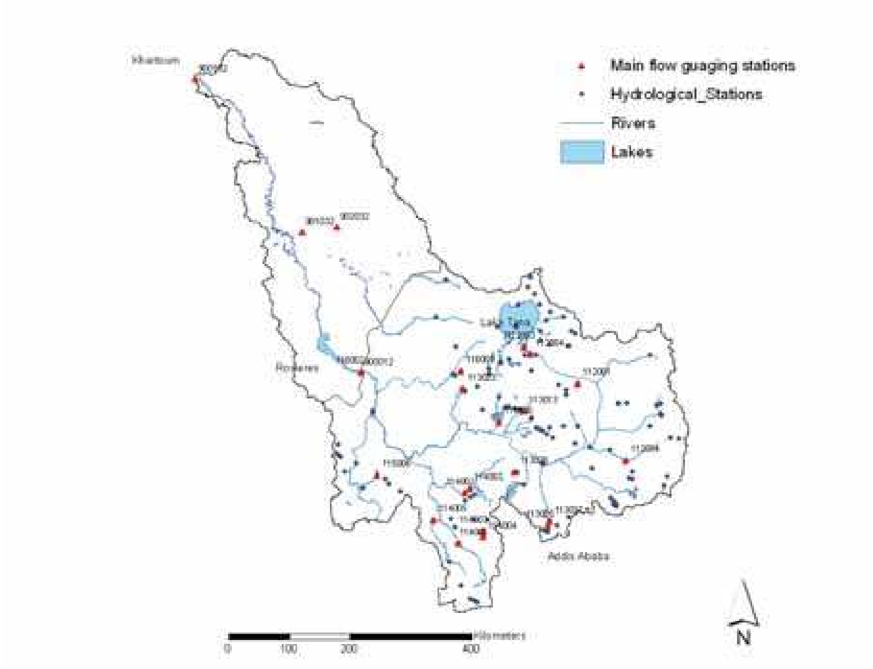


FIGURE 15. Flow gauging stations located in the Blue Nile Basin.

TABLE 8. Summary details of key flow gauging stations in the Blue Nile Basin.

	Station no.	River	Location	Latitude	Longitude	Catchment area (km^2)	Start of record	End of record
				Ethiopia				
1	112003	Abay	Outlet of Lake Tana	11.60	37.38	15,321	1959	-
2	112001	Abay	Nr. Kessie	10.07	38.18	65,784	1959	-
3	116002	Abay	At Sudan border	11.23	34.98	172,254	1959	-
4	112004	Andassa	Nr. Bahar Dar	11.50	37.48	517	1959	-
5	112034	Jemma	Nr. Lemi	9.92	38.90	5,412	1986	-
6	113005	Guder	At Guder	8.95	37.75	524	1959	-
7	113013	Birr	Nr. Jiga	10.65	37.38	978	1959	-
8	113023	Dura	Nr. Metekel	10.98	36.48	539	1961	-
9	113026	Neshi	Nr. Shambo	9.75	37.25	322	1963	-
10	113036	L. Fettam	At Galibed	10.48	37.02	757	1986	-
11	113037	Debis	Nr. Guder	9.02	37.77	799	1988	-
12	114001	Didessa	Nr. Arjo	8.68	36.42	9,981	1959	-
13	114002	Angar	Nr. Nekemite	9.43	36.52	4,674	1959	-
14	114003	Sifa	Nr. Nekemite	8.87	36.78	951	1960	-
15	114004	Wamma	Nr. Nekemite	8.78	36.78	844	1960	-
16	114005	Dabana	Nr. Abasina	9.03	36.05	2,881	1961	-
17	114007	Little Ang	At Angar Gutin	9.50	36.58	3,742	1977	-
18	115006	Sechi	Nr. Mendi	9.70	35.22	562	1979	-
19	116005	Beles	At Bridge	11.25	36.45	3,431	1981	-
				Sudan				
20	900152	Nile	Khartoum	15.6	32.52	325,000	1904	-
21	902032	Rahad	Hawata	13.4	34.62		1971	-
22	901032	Dinder	Giwasi	13.32	34.10		1971	-
23	900012	Nile	Rosieres	11.23	34.98	210,000	1962	-

Source: Ministry of Water Resources, Ethiopia and Ministry of Irrigation and Water Resources, Sudan

Table 9 and Figure 16 illustrate the differences in mean monthly flow and runoff at four gauging stations located along the Blue Nile. The gauge at Rosieres is located upstream of the reservoir, very close to the national border. The data show that at all locations flow is heavily concentrated in the summer months (i.e., July to October).

TABLE 9. Mean monthly flow (Mm^3) and runoff (mm) measured at gauging stations located on the main stem of the Blue Nile.

Location		Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Lake Tana	Mm^3	203	127	94	70	49	45	114	434	906	861	541	332	3,776
	mm	13	8	6	5	3	2	7	28	59	56	35	22	244
Kessie	Mm^3	331	221	227	211	209	258	3,003	6,594	3,080	1,456	788	503	16,881
	mm	5	3	4	3	3	4	46	100	47	22	12	8	257
Rosieres	Mm^3	762	446	364	324	612	1,659	6,763	15,228	12,111	6,484	2,559	1,348	48,660
	mm	4	2	2	2	3	8	32	73	58	31	12	6	233
Khartoum	Mm^3	724	448	406	427	503	1,084	4,989	15,237	13,625	7,130	2,451	1,257	48,281
	mm	3	2	2	2	2	4	18	55	50	26	9	5	178

Source: Ministry of Water Resources, Ethiopia; Sutcliffe and Parks (1999)

(a) (b)

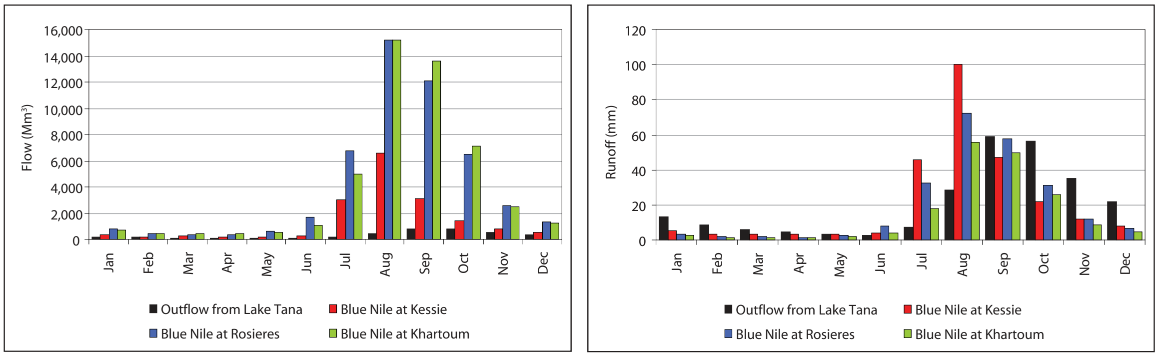


FIGURE 16. a) Mean monthly flow (Mm^3), and b) runoff at gauging stations located on the main stem of the Blue Nile.

The mean annual outflow from Lake Tana is 3,776 Mm^3 with a range from 1,075 Mm^3 in 1984 to 6,182 Mm^3 in 1998. The average annual outflow equates to 257 mm over the total catchment area of 15,321 km^2. The mean annual rainfall over the basin is estimated to be 1,342 mm (Melkamu 2005). So, this gives a coefficient of runoff of approximately 18%. The natural seasonal distribution is slightly attenuated by the lake storage, with peak flows delayed from August to September/October and proportionally higher dry season flows than along the rest of the river[4]. Since 2001, the outflow from Lake Tana has been controlled by the Chara Chara Weir which was built to regulate flow for hydropower production. This has resulted in a change in the natural pattern of flow from the lake, with higher dry season flows and lower wet season flows (Figure 17). However, because the flow from Lake Tana is a relatively small proportion of the flow at Kessie (22%) and an even smaller proportion of the flow at the border (i.e., Rosieres) (8%), the regulation is not thought to have had a significant impact on the distribution of flows downstream.

[4]Natural dry season flows equate to 39% of total flow at the Lake Tana outlet, compared to approximately 15% at the other locations along the Blue Nile.

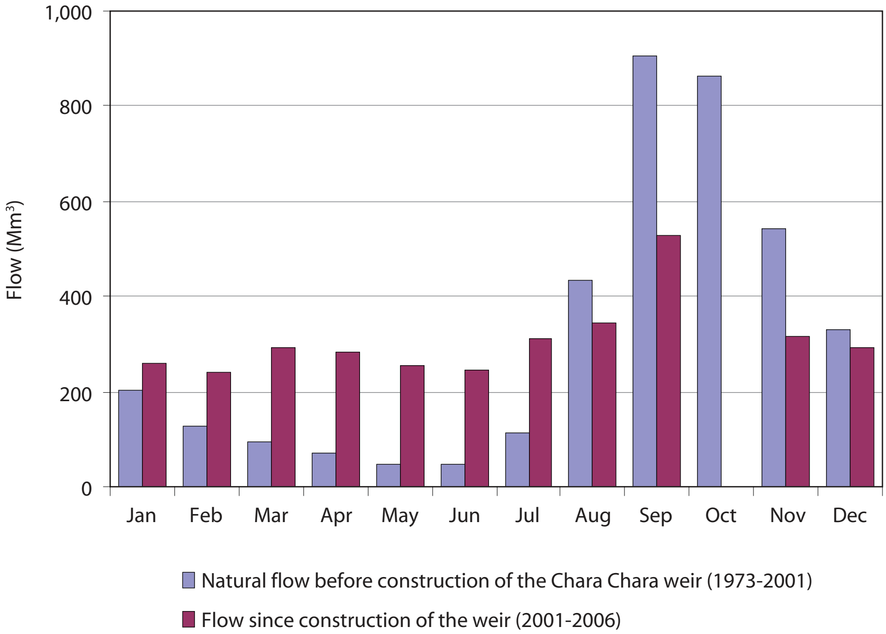


FIGURE 17. Modification of outflow from Lake Tana as a consequence of regulation by the Chara Chara Weir.

The average annual flow of the Blue Nile at the border of Sudan is 48,660 Mm^3 (excluding Dinder-Rahad). This represents approximately 40% of Ethiopia's total surface water resources of 122,000 Mm^3 (World Bank 2006). The catchment at this location is about 200,000 km^2, so this equates to an average annual runoff of 243 mm (i.e., a coefficient of runoff of approximately 14%).

Despite inflows from the Dinder and Rahad[5] the average annual flow of the Blue Nile at Khartoum (i.e., 48,281[6] million cubic meters) is slightly less that at the border. The catchment at this location is 311,548 km^2, so this equates to an average annual runoff of 155 mm (146 mm if 331,000 km^2 is taken). The reduction in flows between the border and Khartoum, despite the increased catchment area, is a consequence of both water abstractions (for irrigation and water supply, primarily to Khartoum) and high transmission losses. It is estimated that annual transmission losses (i.e., both evaporation and percolation) between Roseires and Khartoum are about 2,000 Mm^3, with an additional 500 Mm^3 from the Sennar and Roseires reservoirs (Sutcliff and Parks 1999).

In addition to seasonal variation in flow there is also considerable inter-annual variation, reflecting significant differences in rainfall. The annual discharge for the Blue Nile at Khartoum from 1920 to 2006 is shown in Figure 18. Between 1920 and1960 the annual discharge oscillated around the mean. From 1960 to 1984 there was a general decrease in discharge, with the flow in most years being below the mean. After 1985, flows have gradually increased (Ahmed 2006; Hydrosult Inc et al. 2006b).

[5] Average annual inflows from Dinder and Rahad are 2,797 and 1,102 Mm^3, respectively. But in both rivers, flows are highly concentrated in the months of July to October (Sutcliffe and Parks 1999).

[6] Also note that Figure 18 provides the medium term average of the Blue Nile, 48,857 Mm^3 at El Deim.

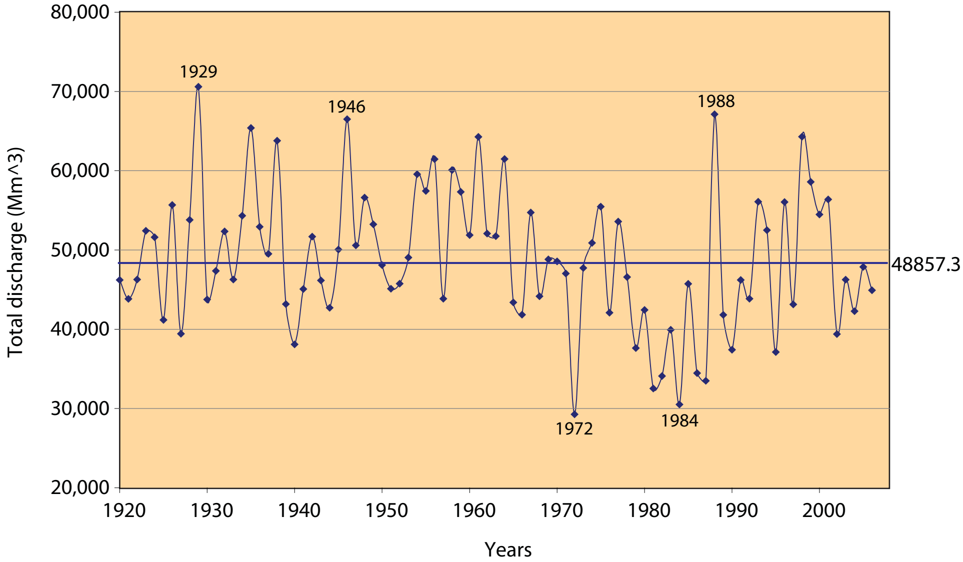


FIGURE 18. Hydrograph of the Blue Nile at El Deim 1920-2006 (Mm^3) (*Source:* Ahmed and Ismail 2008).

3.2. Hydrological Models

In recent years, the number of models simulating the discharge from watersheds in the Blue Nile and other river basins in Ethiopia and Africa has increased exponentially. An overview of the models used in the Nile and Blue Nile is given in Appendix 3. Several other models are also available in the grey literature and published in students' theses and dissertations. Notable here is the work of Seleshi B. Awulachew and Yilma Sileshi and their graduate students.

Most of the models tested in Ethiopia were originally developed for applications in temperate regions. Relatively simple engineering approaches such as the Rational Method have been used (Desta 2003), as well as complex models such as the Precipitation Runoff Modeling System (PRMS) (Legesse et al. 2003), Water Erosion Prediction Project (WEPP) (Zeleke 2000), the Agricultural Non-Point Source model (AGNPS) (Haregeweyn and Yohannes 2003; Mohammed et al. 2004) and water balance approaches (Ayenew and Gebreegziabher 2006). Implementation of these models yielded mixed results. The Agricultural Non-Point Source Model (AGNPS) was tested in the highlands in the Augucho Catchment but could not reproduce observed runoff patterns. The Precipitation-Runoff Modeling System (PRMS) was similarly tested by Legesse et al. (2003) for South Central Ethiopia, and needed extensive calibration to predict the monthly runoff. Ayenew and Gebreegziabher (2006) fitted a spreadsheet type water balance to predict water levels in Lake Awassa in the Rift Valley, but found that the model did not perform well in recent years, possibly due to changing land use. Finally, Hengsdijk et al. (2006) applied a suite of crop growth, nutrient balance, and water erosion models and concluded that common conservation practices such as bunds, crop mulching, and reforestation may actually result in lower overall crop productivity in the highlands of northern Ethiopia. In response to Hengsdijk's conclusions, Nyssen et al. (2006) compared Hengsdijk's predictions with field observations from the same region and found that the models overpredicted crop yields while under-predicting soil losses.

Many simple water balance type approaches have been attempted for the Nile Basin. Both Mishra and Hata (2006) and Conway (1997) developed useful results with grid-based water balance models for the Blue Nile Basin using monthly discharge data from the El Deim Station in Sudan, located close to the Ethiopian border. They were studying the spatial variability of flow parameters and the sensitivity of runoff to changes in climate. Using a water balance model Kebede et al. (2006) concentrated on Lake Tana and developed a water balance utilizing relatively long durations (more than 30 years) of data for precipitation, evaporation, inflows of major tributaries and outflows to the Blue Nile. They calibrated the model using observed lake levels and deduced that lake levels remained relatively constant while outflows from the lake reflected the variation in rainfall (Kebede et al. 2006).

Johnson and Curtis (1994) utilized short-duration (less than 4 years) discharge data from several smaller basins throughout the Blue Nile Basin for the development of a monthly water balance model to better understand the rainfall-runoff relationships. The intention was to use the model for forecasting and to develop a method for calibrating water balance coefficients for small basins lacking available data. Very few other examples of small-scale water balance modeling in the Blue Nile Basin have been published.

Several attempts have been made to evaluate the likely implications of climate change on river flows (e.g., Conway and Hulme 1996; Yates and Strzepek 1998). All of these attempts have been based around relatively simple (often grid-based) rainfall-runoff models, such as WATBAL (Yates 1996).

The main conclusion of this overview of hydrological models used in the highlands of Ethiopia is that the daily simulation results of the more complex models is disappointing when compared with the relatively better predictions of the simple water balance models. The main reason is that the complex modeling techniques, which are typically developed for conditions in the United States or Europe, are not appropriate for Ethiopia. In Ethiopia, the extreme temporal and spatial variability in rainfall and the prolonged dry season mean that hydrological processes are different to those typically encountered in more temperate climates. The lack of available data for both input and calibration further hinders the use of complex models in Ethiopia. For these reasons, simple water balance models, that most efficiently utilize the available data, are the most appropriate choice for simulation of the hydrology of the Blue Nile.

3.3. Runoff Mechanisms

In order to develop better models, knowledge of the basic runoff mechanisms is necessary. To gain insight into these mechanisms Liu et al. (Forthcoming) studied rainfall-runoff patterns in three small watersheds located near or in the Blue Nile Basin. Runoff response patterns were investigated by plotting, the biweekly sums of discharge as a function of effective rainfall (i.e., *P-E* for a two week period) during the rainy season and dry season. An example for one of the watersheds is given in Figure 19. The results indicate that the runoff response changes as the wet season progresses, with precipitation later in the season generally producing a greater fraction of runoff. As rainfall continues to accumulate during a rainy season, each watershed eventually reaches a threshold point where runoff response can be predicted by a linear relationship with effective precipitation, indicating that the proportion of the rainfall that became runoff was constant during the remainder of the rainy season. An approximate threshold of 500 mm of effective cumulative rainfall, *P-E*, was selected after iteratively examining rainfall versus runoff plots for each watershed. This relationship is shown in Figure 20 for the three watersheds studied by Liu et al. (Forthcoming). Despite the great distances between the watersheds and the different watershed characteristics, the runoff response was remarkably similar in each case.

The reason for the similarity in the runoff response among these three watersheds after the threshold rainfall was reached is an interesting question to explore. It is imperative, therefore, to look at various timescales, since focusing on just one type of visual analysis can lead to erroneous conclusions. For example, looking only at storm hydrographs of the rapid runoff response prevalent in the typically intense monsoonal type Ethiopian storms, one could conclude that infiltration excess is the primary runoff generating mechanism (Horton 1933). However, looking at longer timescales in Figure 19, it can be seen that the ratio of *Q/(P-E)* is increasing with cumulative precipitation. Consequently, the watersheds behave differently depending on how much moisture is stored in the watershed. This suggests that saturation excess processes play an important role in the watershed runoff response. If infiltration excess was controlling runoff responses, discharge would only depend on the rate of rainfall, and there would be no clear relationship with antecedent precipitation as is clearly the case in figures 19 and 20. The finding that saturation excess is occurring in watersheds with a monsoonal climate is not unique. For example, Hu et al. (2005), Lange et al. (2003) and Merz et al. (2006) found that saturation excess could describe the flow in a monsoonal climate in China, Spain, and Nepal, respectively. There are certain previous observations for Ethiopia on the suitability of these types of saturation excess models to predict runoff. Awulachew (2000, 2001) used the MoWBAL model for Rift Valley Lakes Basin and the same model was later applied by Tesfahun et al. (2006) for the Blue Nile. Other observations by Zeleke (2000) also suggested saturation excess as the primary mechanism for runoff generation. Attempts to fit regular models based on infiltration excess principles result in extremely poor fits (Haregeweyn and Yohannes 2003). This does not mean that there is no infiltration excess overland flow occurring, and both could occur during high intensity storms. However, as shown by van de Giesen et al. (2000), in the Ivory Coast, a large portion of the overland flow re-infiltrated after the rain stopped before reaching the channel.

Because saturation excess and interflow runoff dominate over the infiltration excess, rainfall intensity is not an important parameter in determining the amount of runoff and, as shown above, models based on a water balance approach are sufficient to describe the hydrology of the Blue Nile Basin in Ethiopia. This confirms the findings of Tesfahun et al. (2006). Therefore, it is recommended to develop such models further.

3.4. Proposed Modeling Strategy for this Study

The question to be answered remains; what simulation model or models should be used for simulating the hydrology of the Blue Nile Basin. Runoff response with water balance type models depends on total rainfall quantity and not intensity. Water balance models are also appropriate because they require minimal input data (e.g., precipitation (P) and potential evapotranspiration (PET) data that are generally available). The only other parameters needed for the water balance model are a soil water storage parameter and a parameter that describes the recession response of the watershed. Both of these parameters are generally available, or can be determined from baseflow separated streamflow. The only other requirement for the water balance model is a methodology to reliably calculate the actual evapotranspiration (AET), given the PET. Several approaches are available for calculating the AET. The method used most often is the Thornthwaite-Mather (1955) approach, where the AET decreases linearly with the soil moisture content below field capacity until the soil reaches the wilting point where the AET is zero. Above field capacity, AET is equal to PET. There

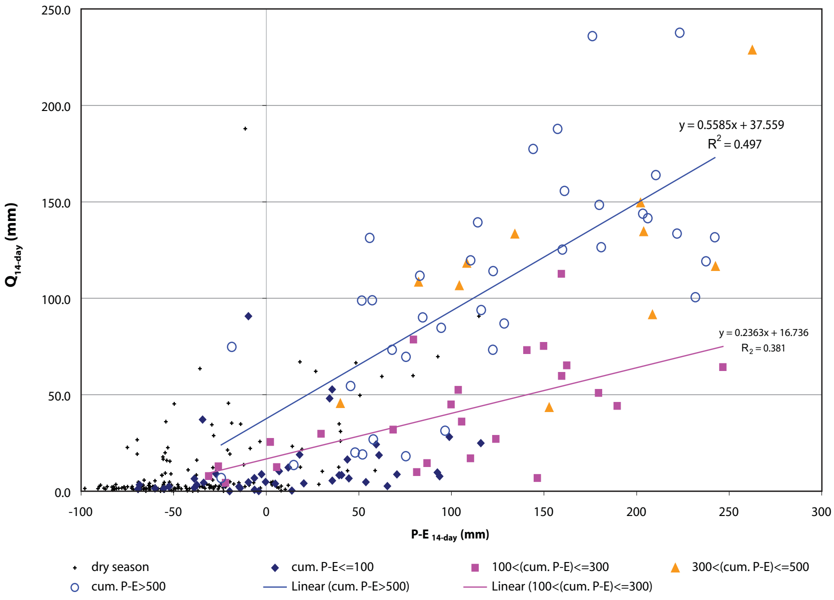


FIGURE 19. Biweekly summed rainfall/discharge relationships for Andit Tid. Rainy season values are grouped according to the cumulative rainfall that had fallen during a particular season, and a linear regression line is shown for the wettest group in each watershed.

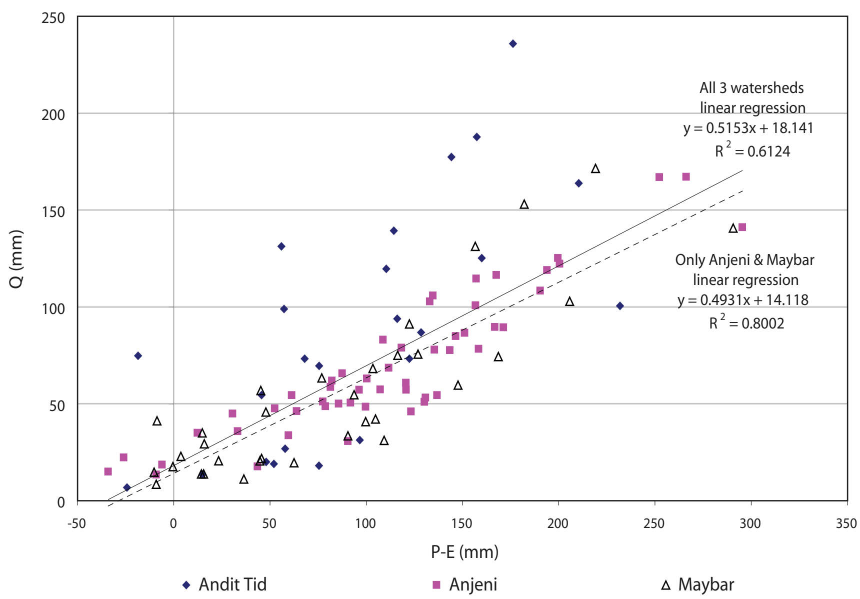


FIGURE 20. Biweekly summed rainfall/discharge relationships for all three watersheds, but only during the latter part of the rainy seasons, after 500 m of cumulative rainfall *(P-E)* has fallen. Linear regressions are provided for the combined plots: all three together are shown with a solid line and only Anjeni and Maybar (together) are shown with a dotted line.

are other approaches to calculate AET, notably, when the linear relationship between field capacity and wilting point is replaced by a piecewise linear or a quadratic expression (Steenhuis and van der Molen 1986), but all methods are essentially similar in their influence on AET. The piecewise method simply results in the soil drying slightly faster than the Thornthwaite-Mather method.

In many water balance model applications, the other parameter, the soil storage, is in most approaches assumed constant over the basin. However, as shown by Liu et al. (Forthcoming) this may not be an appropriate assumption, as the effective soil storage decreases as more and more low-lying areas of the watershed become saturated as the rainfall season progresses. An interesting approach to simulate this phenomenon is developed by Tesfahun et al. (2006) employing a hyperbolic sine function to assure that the soil storage reservoir has to be filled after the dry season before runoff is produced in significant quantities.

The last parameter that is needed to run a water balance model is the baseflow parameter. This determines how fast the water is released by the soil. Several functions have been developed throughout the years for various river basins that can all ultimately be reduced to some kind of power function of the water stored in the watershed. Hillslope reservoirs behave as a zero order reservoir (Stagnitti et al. 2004) while reservoirs that are associated with valley bottoms are either first or second order.

Ultimately, there is a need for additional model development because water balance models only give the discharge at the base of the watershed and do not give the spatial distribution of runoff within the basin. The runoff distribution is especially important for the prediction of erosion and sedimentation. Although many semi-distributed models claim to predict the spatial distribution of runoff, very few have been validated. Moreover, it is unlikely that the lumped basin-scale models (e.g., SWAT, EPIC, WEPP, etc.) predict the runoff distribution correctly, because they are based on the Soil Conservation Service - Curve Number (SCS-CN), which uses soil type and vegetation characteristics to determine the runoff and not the topography as should be the case in the Ethiopian Highlands. Distributed saturation excess models such as TOPMODEL (Beven et al. 1984), the Soil Moisture Distribution and Routing (SMDR) model (Johnson et al. 2003; Gérard Marchant et al. 2006; Hively et al. 2006; Easton et al. 2007), and the Variable Source Loading Function (VSLF) (Schneiderman et al. 2007) model could all, potentially, be applied to the Ethiopian portion of the Blue Nile to yield satisfactory results. However, all have extensive data needs, and thus may be infeasible. Recently, Easton et al. (2008) re-conceptualized the Soil and Water Assessment Tool (SWAT) model to correctly predict the distribution of saturation excess runoff. Hence, there is the potential to utilize SWAT.

It is possible that using several models in combination may produce the best results. Current understanding of the hydrology could be enhanced using a combination of model predictions and a modified version of SWAT which incorporates the changes made by Easton et al. (2008) as well as modifications currently being implemented that include better simulation of watershed behavior.

4. SOIL EROSION AND SEDIMENTATION

4.1. Background

Soil erosion is a major watershed problem in many developing countries. In a watershed there may be many different sources of erosion. Eroded material derived from the watershed, riverbed and banks will be transported with the flow as sediment transport, either in suspension or as bed load. Ultimately, this sediment is redeposited, often causing problems in downstream areas.

Generally, the sediment transport phenomenon is a function of many processes. Erosion of the land surface takes place in the form of sheet erosion, rill and inter-rill erosion, and gulley erosion. Eroded sediment particles that are transported to the river are called delivered sediment or sediment yield from a given watershed. The delivered sediment travels with the flow as suspended material. The other component of the sediment transport comes from the bed and bank material and travels with the flow as suspended or bed load. The transported particles move downstream as far as the hydraulic conditions permit. These conditions depend on the slope of the river, velocity, discharge, cross sections, etc.

Throughout Ethiopia, soil loss is a critical problem. Sheet and rill erosion, is estimated to be very high, reaching levels of up to 100–200 Mt ha^{-1} yr^{-1}, in 50% of agricultural areas (Sonnenveld 2003, quoting the earlier works of Hurni; and Herweg and Stillhardt). Population densities and herd sizes are the highest in Africa, and continue to grow rapidly. Thus, without careful land management, erosion rates are likely to increase.

4.2. Erosion and Sediment Problems in the Blue Nile

According to Hydrosult Inc et al. (2006b), the Ethiopian Plateau is the main source of the sediment in the Blue Nile system. Some erosion occurs within Sudan, mainly on and around the rock hills (*Jebels*), which have become devoid of vegetative cover. Most of this is deposited on the foot slope of the hills and does not enter the drainage system. Some water induced soil movement also occurs on the flat clay plains, but given the poorly developed surface drainage system little of this sediment reaches the main rivers. However, those streams which do reach the river during the rainy season carry heavy sediment loads. Within Sudan, although there is not enough information, however, it is believed that about 11 seasonal streams upstream of the Roseires Dam bring a considerable amount of sediment load during the rainy season (Ahmed 2006).

There are four main areas of high sheet erosion in the Abay Basin (Hydrosult Inc et al. 2006b). The first is the steep slopes around Mount Choke in East and West Gojam. This is an area of high rainfall which, because of the problems of providing effective water disposal structures, causes problems in developing physical soil conservation structures. The second area of high erosion hazards occurs in the Lake Tana Basin. This area includes the steep cultivated slopes around mounts Guna (South Gonder) and Molle (South Wello). A third, more restricted, area is found in the upper Jema Sub-basin in South Wello on the high hills north and west of Debre Birhan. A fourth area is located south of the Abay and encompasses the upper and middle steep and cultivated slopes of the Middle Abay Gorge in East Wellega. Two subsidiary areas with a high erosion hazard are the Upper Didessa Valley and along the escarpment hills to the west of Lake Tana in the upper Dinder and Beles valleys.

The total soil eroded within the landscape in the Abay Basin is estimated to be 302.8 million tonnes per annum and from that cultivated land[7] is estimated to be 101.8 million tonnes per annum. Thus, about 66% of soil being eroded is from non-cultivated land (i.e., mainly from communal grazing and settlement areas). The area of cropland subject to "unsustainable" losses (i.e., where loss exceeds soil formation or 12.5 tonnes/ha/yr) are 968,900, 104,000 and 956,900 ha in the Amhara, Benishangul Gumuz and Oromiya areas of the Basin, respectively. Thus, a total of about 2.03 million hectares (Mha) of cultivated land have unsustainable soil loss rates.

[7] "Cultivated land" as identified on the 1:250,000 landsat images. This may include areas of grassland, settlement, field boundaries, etc., that are too small to discriminate separately. Invariably "cultivated" land is greater in area than land under crops as defined, for example, by the Central Statistical Office (CSA).

Of the total 302.8 million tonnes of soil eroded, a proportion is re-deposited within the landscape, but the remainder reaches streams and rivers. At the basin level, the estimated sediment delivery ratio (SDR) indicates that approximately 55% of sediment remains in the landscape and does not reach the stream system. This estimate is much lower than the 90% estimated by the Ethiopian Highlands Reclamation Study (EHRS) but closer to the 70% estimated by Hurni (1985).

The main erosion problem in the Sudan part of the Blue Nile Basin is the gully erosion along the Blue Nile and Dinder rivers. The plains are overlain with Vertisols (black cracking clays). The Vertisols develop very wide cracks during the dry season. At the onset of the rains water enters the cracks. Whilst the soils are covered with deep rooted vegetation there is no problem as roots take up any excess subsurface water. However, once this vegetation is removed there is excess water in the soil and subsurface tunnels develop. These eventually collapse leaving an incipient gulley, which gradually extends back into the plain stripping the soil away from the underlying weathered rock of unconsolidated sediments. These unconsolidated sediments are extremely soft and erodible and deep gullies form very quickly resulting in what is known locally as *kerib* land.

The Dinder is gullied for about 50 km upstream from its confluence with the Blue Nile. Most kerib land along the Dinder has gullied up to 500 m from the river. The Rahad River does not appear to be affected except very locally near its confluence with the Blue Nile. An interpretation of Landsat TM imagery from the year 2000 provided an estimate of 141,810 ha of land in the Blue Nile Catchment of Sudan being affected. Some kerib land adjoins rainfed and some irrigated cropland. As no information is available on erosion rates it is difficult to estimate the impact on loss of cultivated land (Hydrosult Inc et al. 2006b).

4.3. Erosion and Sediment Data

Information concerning the sediment load of the Nile is limited compared with the available discharge data. Some measurements of suspended sediment load are available, but measurements of bed load are very rare. According to the information obtained from the Ministry of Water Resources (MoWR) in Ethiopia, and Hydrosult Inc et al. (2006b), the MoWR has a number of intermittent sediment records for tributaries of the Abay. Nearly all watersheds for which data are available are less than 1,000 km^2 in area. The data have been analyzed and tabulated by three sources: (i) The Abay Basin Master Plan Study, (ii) the Tekeze Medium Hydro Study, and (iii) a study undertaken by Rodeco for MoWR (2002). There are a number of discrepancies between the datasets and some stations are included in one dataset but not in the others.

Examination of the sediment stations available from the Hydrological Department of the MoWR shows that there are a total of 45 in the Abay Basin. However, some of these have only very sporadic measurements. Most of the available sediment data is related to periods during which stage-discharge relationships were developed for flow gauging stations or when revisions to such relationships were made. A few special studies have also been undertaken. Continuous monitoring of sediment has not been undertaken at any of the stations. A consolidated list of stations with data records for the Abay is provided in Appendix 4.

Preliminary analysis shows that sediment distribution is having a strong peak during the rainy season, particularly in the month of July and almost no sediment in the dry seasons. Figure 21 and 22 show examples of the sediment concentration profile of the Ribba watershed and the aggregated information of three sub-basins of the Upper Blue Nile, respectively. Since the stage or discharge with sediment relation ship is weak particularly during dry seasons, stage-discharge like relationship for sediment is therefore not applicable for sediment data generation. According to Haregeweyn et al. (2005), analyses of the data indicate that there is no clear relationship between sediment yield and the size of the watershed area. This suggests that a number of other factors have a much stronger influence. In a study undertaken in the Tekeze Basin these other factors were found to be variations in lithology, land use, gully density and connectivity. Given the similar conditions in the Abay Basin the same factor are also likely to be responsible, in addition to the rainfall intensity and land topography.

As examples, figures 21 and 22 show the sediment discharge curves for the year 2000 for two rivers in the Lake Tana Catchment.

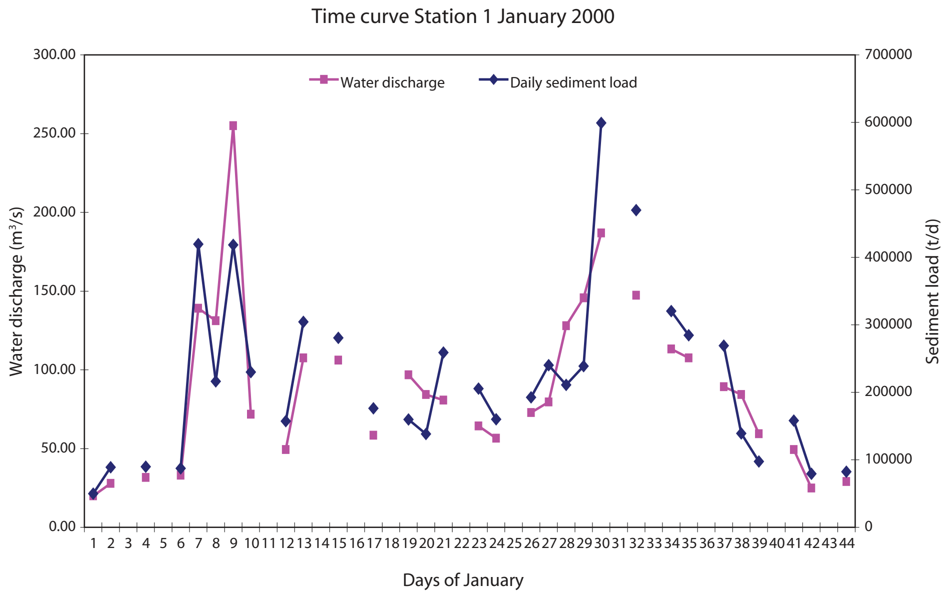


FIGURE 21. Sediment discharge curve at Addis Zemen (Ribba).

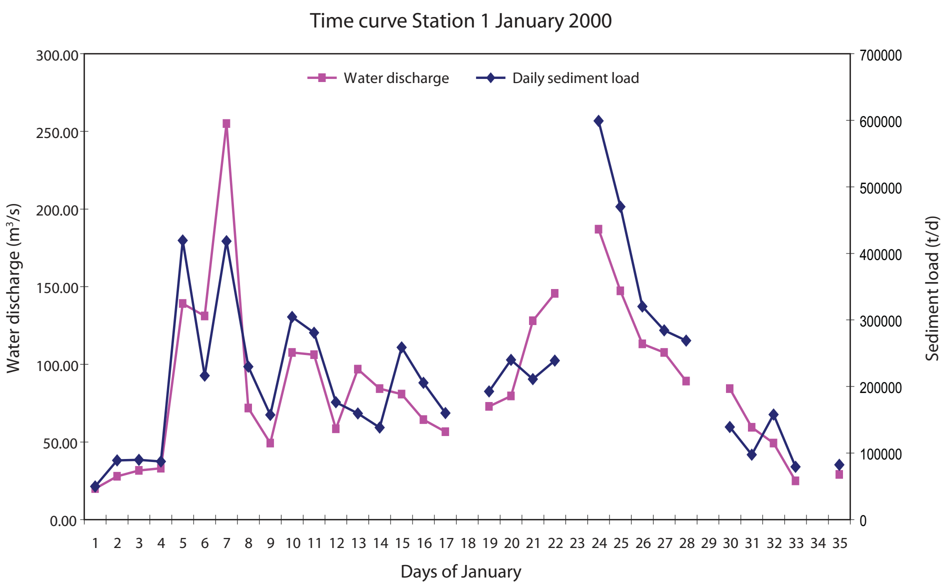


FIGURE 22. Sediment discharge curve at Guder (Bello) station.

In the Sudanese part of the catchment, intensive sediment measurements were started in 1988 and 1996 to quantify the sediment entering the Gezira and Rahad schemes, respectively. Measurements were taken on the Blue Nile (1954 and 1955 at Wad Alais) as part of the studies for the Roseires Dam. Following construction of the dam, further sedimentation studies have been undertaken (i.e., sediment load measurements and bathymetric reservoir surveys) to estimate reservoir siltation. At present a limited number of sediment monitoring stations are operating at various places (see Appendix 3). These measuring stations are at El Deim, Wad Alais and Sennar on the Blue Nile; Gawisi and Hawata on the Dinder and Rahad rivers, respectively. Furthermore, some stations are located on the Gezira and Rahad schemes, and Hamdab on the main Nile. Table 10 summarizes the 10-day mean sediment concentration for the Blue Nile River at different locations in Sudan and Table 11 shows the maximum sediment load concentration for a selected flood event in 2002. Because of the limited data available for most of the locations, the estimates of sediment load and concentration may be subject to a wide range of errors.

TABLE 10. Ten-day mean sediment concentration for the Blue Nile at different locations in Sudan.

Month	Period	Mean sediment concentration (part per million (ppm)		
		El Deim	Wad Alais	Sennar
June	II	1,956	1,172	-
	III			
July	I	3,361	2,454	3,200
	II	3,895	2,724	4,072
	III	4,335	3,274	3,612
August	I	5,660	2,772	2,790
	II	3,095	2,859	2,415
	III	2,948	2,654	2,154
September	I	3,589	2,588	1,887
	II	2,305	1,669	1,500
	III	1,755	1,028	1,442
October	I	1,294	990	900
	II	591	946	-
	III	317	-	-

TABLE 11. Maximum sediment concentration during the flood season 2002 in different locations of the Blue Nile System.

Station	Maximum concentration (ppm)	Date
Roseires	21,570	29/7/2002
Wad Elais	15,044	06/8/2002
Sennar	12,459	30/7/2002
Wad Medani	10,106	16/7/2002
Gezira Canal	19,472	31/7/2002
Managil Canal	21,535	31/7/2002

4.4. Estimate of Sediment Inflow to Sudan

Unlike discharge, sediment rating curves are usually based on short data records. However, long-term sediment load estimates are required for reservoir sedimentation studies and to assess trends in sediment loads resulting from land use changes. The procedure developed by Miller (1951), which combine short term sediment rating curves with long-term flow duration curves was implemented in the Nile Basin Capacity Building Network (NBCBN) study. Flow durations curves for thirty years (1966-1995) were developed for each 10-day period of the flood months (July-September) for the El Deim gauging station. Suspended sediment concentrations were then computed with the aid of the appropriate sediment-rating curve. These values were then multiplied by the corresponding time interval and time accumulated to give the mean sediment yield over each period.

4.5. Summary of Sediment Results from Previous Studies on the Blue Nile

A number of previous studies of sediment transport have been conducted on the Blue Nile. As part of the Nile Friend project (Sediment Transport component) a comparison was made between the discharge measured at El Deim, the total rainfall over the watershed and the sediment concentration in the Blue Nile (Figure 23).

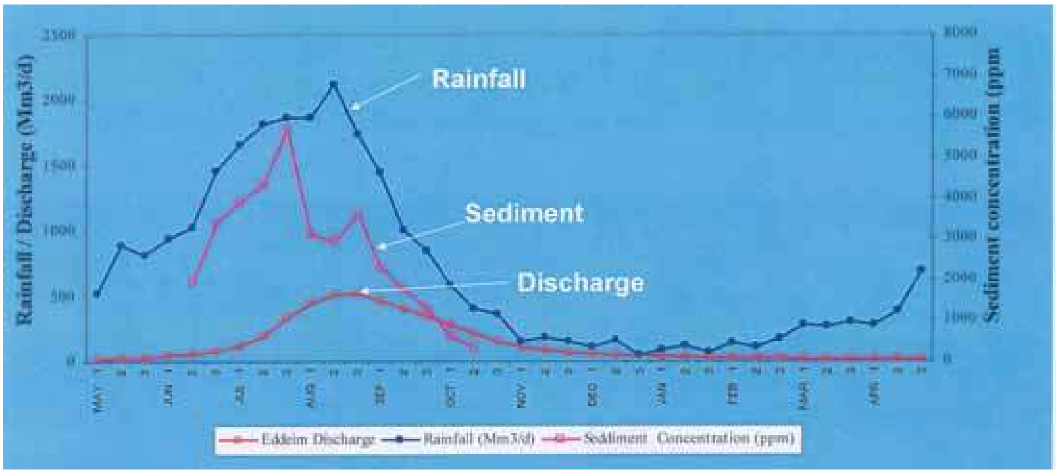


FIGURE 23. Comparison between rainfall, discharge and sediment yield at El Deim (*Source:* Ahmed 2003).

The results show that the peak of the discharge (513 Mm^3 per day), comes after the peak of the sediment (5,660 ppm) by about three weeks, while the peak of the total rainfall (2,123 Mm^3 per day) comes one week before the peak of the discharge. This sequence of incidents is logical. It is attributed to the fact that at the beginning of the rainy season, the catchment area is bare, there is little green vegetation and the soils are exposed and easily eroded. The time lag between these peaks depends on the rainfall intensity, duration and temporal distribution as well as on the condition of the catchment.

The deforestation and the degradation of the Ethiopian Highlands have a negative impact on the whole downstream catchment. In Sudan, sediment deposition in the reservoirs and the irrigation canal networks causes flood risks, crops damage, pump intake blockages, reduced production and hydropower generation difficulties. The cost of desilting reservoirs and irrigation canals is enormous (Figure 24).

FIGURE 24. Dredging in Roseires Reservoir and an irrigation canal in Sudan (*photo credit:* Seleshi B. Awulachew).

4.6. Reservoir Sedimentation and Potential Mitigation Measures

The reservoirs on the Blue Nile are seriously affected by sedimentation. The Sennar Dam, constructed in 1925, was the second dam built on the Nile system, after the Old Aswan Dam in Egypt (1902). The original capacity of the Sennar Reservoir was 930 Mm^3. Because of its good design and the proper implementation of operational rules (i.e., allowing the early floods to pass through the dam), as well as relatively low sediment input because of less upstream degradation, there was relatively little sedimentation in the reservoir during the first 56 years (i.e., 1925-1981) (Figure 25). Throughout that period the rate of sedimentation never exceeded ½% per year (i.e., 4.6 Mm^3). Consequently, there was only a 28% reduction in the reservoir capacity over the first 56 years. However, between 1981 and 1986 the rate of sedimentation increased dramatically to a rate of 80 Mm^3 per year (i.e., a reduction of 400 Mm^3 (43%) in only 5 years). In total, over a period of 61 years the Sennar Dam lost 660 Mm^3 (i.e., 71% of its original capacity). Although some of the rapid increase can be attributed to increased sediment loads, the primary reason for the huge rise in the period 1981 to 1986 was due to a change in the operational rules to satisfy the requirements of new irrigation schemes located upstream and downstream of the dam. Currently, the Sennar Reservoir is no longer used to store significant volumes of water, but instead provides minor regulation to generate a limited amount of hydropower (15 MW).

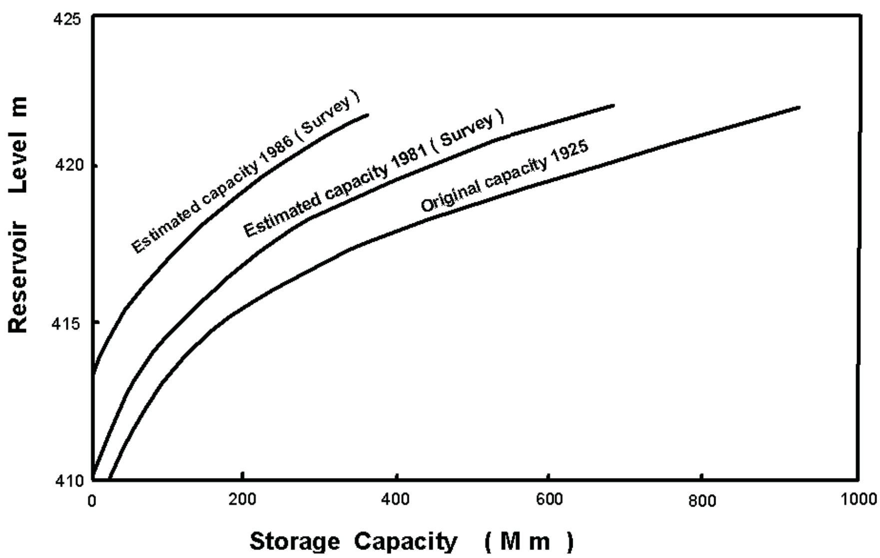


FIGURE 25. Storage capacity versus reservoir level of Sennar Dam (1925-1986) (*Source:* Ahmed 1992).

The Roseires Dam, which was constructed in 1964 on the Blue Nile, is the biggest reservoir in Sudan, with an initial capacity of 3,300 Mm^3. The Roseires Dam is located about 200 km upstream of the Sennar Dam. Figure 26 shows the sediment volume and the content of the Roseires Reservoir for the period 1964 to 1992. In the first ten years, the drop in the capacity was 550 Mm^3 with a rate of 55 Mm^3 per year. In the period 1976 to 1981 the reduction in the capacity was 100 Mm^3 with a rate of 20 Mm^3 per year. In the period 1981 to 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 to 1992 with a rate of 60 Mm^3 per year and a total reduction of 427 Mm^3. This, may be attributed to the drought which took place during the late eighties and the policy of food security adopted in Sudan. This resulted in an increase in the irrigated area but no consideration was given to mitigation measures and the water required to flush out silt from the reservoirs and the irrigation canal networks. In total, in the 28 year period from 1964 to 1992, more than 36% (1,200 Mm^3) was lost from the original reservoir capacity. This reflects a rate of deposition that was significantly greater than the 15 Mm^3 per year predicted by the dam designer (Sir Alexander Gibb & Partners). Since 1992, there has been no bathymetric survey of the reservoir, so it is not possible to know the current situation. However, it is almost certain that significant volumes of sediment have been deposited in the reservoir in recent years, though it is possible that an equilibrium has been established. Figure 27(a) and (b) show sediment and debris deposited in front of the Roseires Dam.

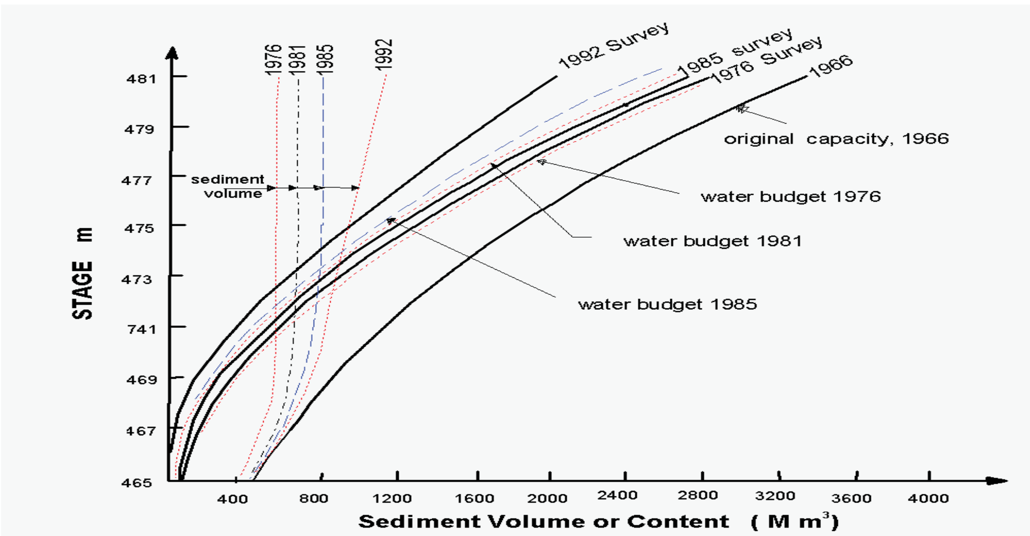


FIGURE 26. Sediment volume and content of Roseires Dam (*Source*: Ahmed 2006).

Figure 27(a). Delta formation upstream, Roseries Dam (*Photo:* Ahmed 2005); **(b)** Debris in the reservoir upstream, Roseries Dam (*Photo:* Ahmed 2005).

Clearly, methods to control sedimentation (e.g., to revise the present operation policy of the reservoirs and seek an efficient flushing system) are essential for both the Rosieres and the Sennar dams. Moreover, it is essential that work is conducted, in collaboration with the upstream area in the Ethiopian Highlands, to reduce the sediment input through better watershed conservation and management. Measures that could be adopted include: catchment erosion control, maximization of sediment through flow (i.e., sluicing), diversion of heavy sediment flow (by passing), and dredging. There is no doubt that the most effective sediment control is through upstream conservation, for example, through green cover (afforestation) and soil and water conservation measures.

4.7. Sedimentation of Irrigation Networks

Sedimentation is a major problem for irrigation systems in Sudan. It creates serious negative impacts such as reduction of irrigated area and decreases in crop productivity. It also increases the cost of operation and maintenance. The sediment is deposited as a result of the low flow velocities experienced in irrigation canals. It is estimated that, in Sudan, almost 97% of the sediment entering the irrigation systems is smaller than 63 microns (i.e., predominantly silt and clay). The kind of soil formed by the deposition of this fine sediment on the bed and banks of canals provides an ideal environment for aquatic weed growth. Such growth reduces flow velocities further, thereby resulting in yet more sediment deposition. Figures 28 and 29 provide an insight into the serious problem facing the Blue Nile irrigation schemes. Figure 29 shows the situation of bad sediment clearance in one of the irrigation canals in the Gezira scheme arsing because of the use of an unsuitable excavation machine. The approximate distribution of sediment deposition, according to recent studies carried out in the Gezira scheme, gives the following results (Ahmed 2006).

Main canal	5%
Major canals	23%
Minor canals	33%
Passed to the fields	39%

In Sudanese irrigation schemes, the most common form of sediment control is dredging of the deposited sediment. This practice is very expensive and time consuming and alternative solutions have been suggested by the National Hydraulics Research Station including (Ahmed 2006):

- to change the present sediment clearance practices;
- to change the water distribution practices; and
- to introduce sediment excluders or settling basins.

However, we believe further studies and investigations are required to better deal with the sedimentation problem in the irrigation canal networks.

FIGURE 28. Sedimentation problem in the Gezira scheme canalization system (*photo credit:* Abdella A. Ahmed).

FIGURE 29. Sedimentation challenges in canals of 80 km Meana to Rahad conveyance. Note the canal is behind the pile of dredged sediment (*photo credit:* Seleshi B. Awulachew).

4.8. The Challenges

Erosion, sediment transport and sedimentation are critical problems in the Blue Nile Basin. The problems are compounded by a range of factors, not only related to the hydraulic properties of the river, but also to various social, institutional and political problems. Erosion and sediment problems are strongly related to land use policy, natural resource management, level of development and degradation/deforestation of the basin as well as cultivation practices, conservation measures, etc. Many of the most pertinent issues are reviewed by Hydrosult Inc et al. (2006b, 2006c). They identified the key issues as follows:

- policy issues and opportunities,
- institutional issues and opportunities, and
- physical and technical issues.

The physical and technical issues include:

- soil erosion and sedimentation,
- soil degradation and loss of agricultural productivity,
- changes in vegetative cover and degradation of wetlands in the catchment,
- the extent of reforestation and increases of vegetation cover in the basin, and
- trends in soil and vegetation degradation, and loss of biodiversity.

Based on these and the previous reviews it is clear that socioeconomic development in the basin, particularly in downstream areas, is hampered by sediment deposition. Future development is likely to be similarly constrained because of the current unprecedented levels of degradation in the upper catchment. It is not only human interventions that are affected, but there is also significant damage to the environment as a consequence of high sediment loads. It is essential that appropriate measures are introduced to reduce erosion. Measures that can be implemented at catchment level can be broadly categorized as conservation measures (i.e., protecting non-degraded areas) and degradation reversal measures (i.e., that reverse degradation in already degraded areas).

4.9. Proposed Modeling Strategy for this Study

The watershed modeling component of the study is focused on the characterization of erosion and sediment transport, and sedimentation issues in the basin, particularly in those upstream areas which are the primary sources of sediment collection. The objective is to assess both the on-site and off-site impacts of possible interventions. The analysis of the impact of interventions, using modeling and scenario analysis, will include evaluation of the impacts on both existing and planned infrastructure.

Modeling sediment and evaluation of the impact of intervention on sediment budgets is a difficult task. There is no known modeling framework which can easily estimate sediment erosion and transport and evaluate the impact of soil and water conservation measures at large scales. Erosion modeling approaches such as Universal Soil Loss Equation (USLE) or Revised Universal Soil Loss Equation (RUSLE) estimate erosion in small catchments based on relationships established using soil conservation data. Applying such relationships to a basin the size of the Blue Nile is difficult, since these models are not designed for such large systems and obtaining the required input data is also difficult. However, in the current study an attempt will be made to use them in selected research catchments such as the Soil Conservation Research Project (SCRP) sites of Anjeni and Tid. Other techniques, based on discharge-sediment rating curves, will be used to establish sediment relationships at larger scales. Directly measured data, such as data from the reservoirs, will be analyzed to provide an insight into the key points of cumulative sediment yield in the basin.

Evaluating the impact of interventions will be difficult. An attempt will be made to collect primary data from soil and water conservation data sites such as the Koga Watershed project sites. Impacts of changes in land use cover will be evaluated wherever appropriate sediment data are available. Remotely sensed data (i.e., satellite data) will be used to assess changes in land cover and this information will be linked to sediment yields to assess the impacts of changes in land cover change on erosion risk. Where possible the SWAT model will be employed for detailed analyses and understanding of the impact of interventions.

Schematically, the entire Blue Nile Basin will be nested to provide an overview and understanding of the sediment dynamics at various scales. Figure 30 provides a schematization of the modeling framework, illustrating the linkages across scales. This will include:

- Micro-watershed level
- Watershed and small dam level
- Sub-basins and major lakes
- Basin outlet and large reservoir
- Downstream of lake outlets and large reservoirs

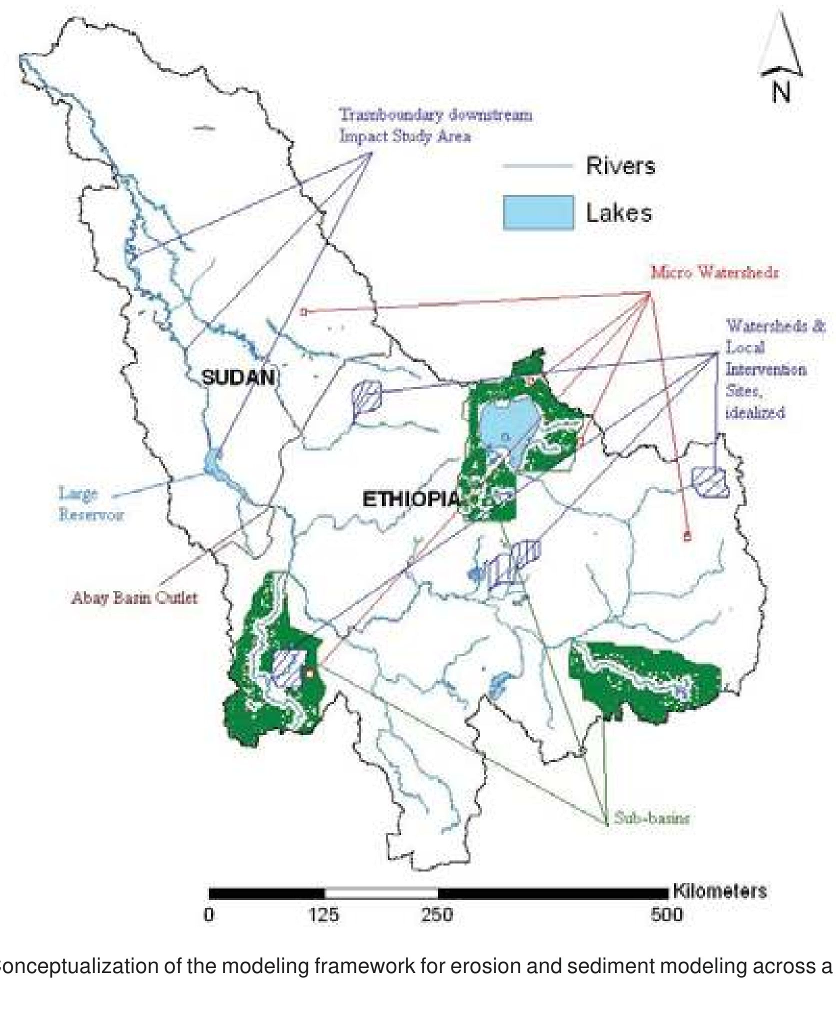


FIGURE 30. Conceptualization of the modeling framework for erosion and sediment modeling across a range of scales.

5. WATER RESOURCES DEVELOPMENT

5.1. Current Situation

Ethiopia currently utilizes very little water of the Blue Nile, because of the inaccessibility of the river, lack of infrastructure, the major centers of population lying outside of the basin and due to its system mainly depending on the rainfed system. To date only two relatively minor hydraulic structures have been constructed in the Ethiopian Blue Nile Catchment (Table 12). These two dams (i.e., Chara Chara Weir and Finchaa) were built primarily to provide hydropower. The combined capacity of the power stations they serve (218 MW) represents approximately 30% of the total currently installed power capacity of the country (i.e., 731 MW, of which 90% is hydropower) (World Bank 2006).

There is very little irrigation in the Ethiopian Blue Nile Catchment. Figure 31 shows the location of existing “modern” irrigation schemes. The total irrigated area is currently estimated to be less than 15,000 ha, but since this does not include the small-scale traditional schemes it is certainly an underestimate of the real total. Currently, the only major irrigation scheme in the Ethiopian part of the catchment is the Finchaa sugarcane plantation (8,145 ha), which utilizes water after it has passed through the hydropower plant (Table 12).

On the other hand, Sudan utilizes significant volumes of water from the Blue Nile, both for irrigation and hydropower production. Both the Sennar and Roseries dams have been constructed on the main river approximately 350 and 620 km southeast of Khartoum (Table 12), respectively. These generate hydropower (primarily for Khartoum) as well as providing water for the large Gezira irrigation scheme. The installed power capacity at the two dams is 295 MW, which represents about 25% of the countries total capacity (i.e., 1,200 MW from both thermal and hydro power stations).

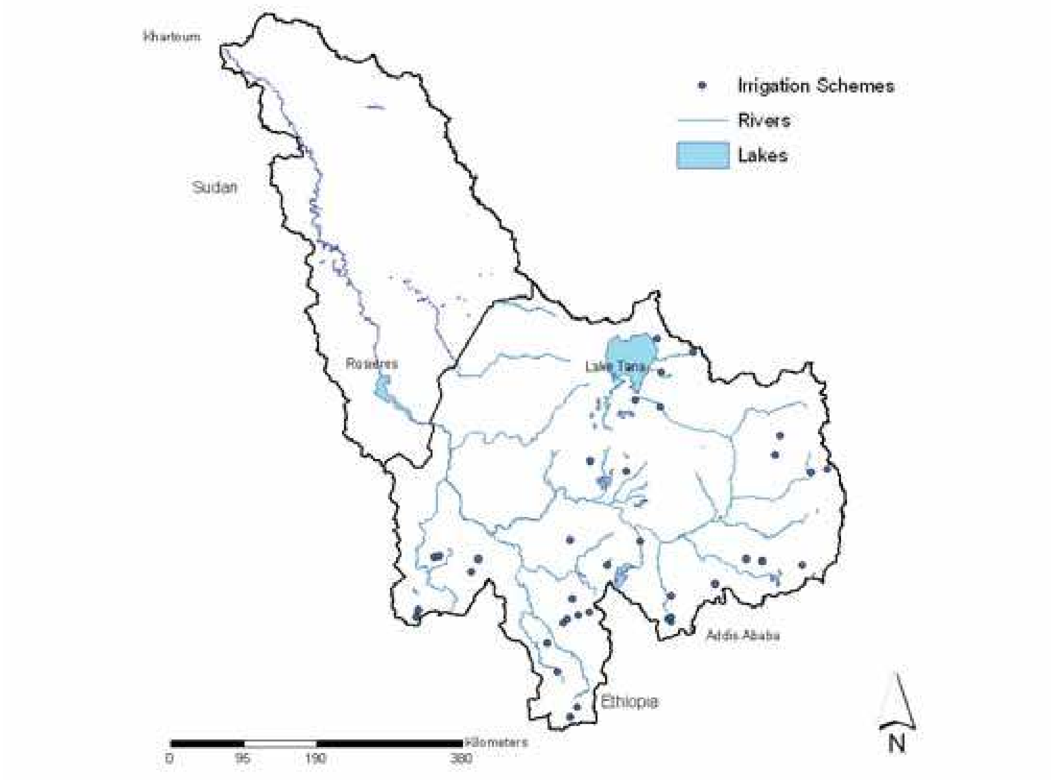


Figure 31. Existing “modern” irrigation schemes in the Ethiopian Blue Nile.

The Gezira scheme, which covers 882,000 ha, is one of the largest irrigation schemes in the world. It lies between the White and Blue Nile rivers, immediately to the south of Khartoum and supports the livelihoods of 100,000 farmers. The Gezira scheme was designed as a supplementary irrigation system from the Blue Nile River. It is worth a mention, that the Blue Nile is the main source of water for more than 70% of the irrigated area in Sudan. The scheme is divided into approximately two halves: the area brought under irrigation between 1925 and 1958, and the Managil Extension developed over the course of the 1960s and the early 1970s. The arid climate necessitates irrigation of both summer and winter crops. This is achieved by diverting water from the Sennar Dam just south of the scheme. Irrigation is primarily by gravity flow. Two parallel canals leave the Sennar Dam and merge into a common pool. From there several branch canals, one main canal and three subsidiary canals diverge westwards to serve Managil (Gezira Extension) and two smaller main canals (old main canal and new one) north into the older part of the scheme. Each of the canals subdivides into branches, major and minor canals of varying sizes (Levine and Bailey 1987). In total there are some 11,000 km of irrigation canals, and 29,000 field channels with 1.5 km each (Ahmed 2003). The scheme is estimated to use 9,226 Mm^3 of water annually and produces two-thirds of the country's cotton exports (World Bank 2000). However, according to official reports from the Ministry of Irrigation and Water Resources of Sudan, the long-term average of Geriza water use is 7,000 Mm^3 annually.

Other irrigation schemes on the Sudanese Blue Nile and its tributaries are presented in Table 13. The estimate for the total area currently irrigated in the Blue Nile Catchment of Sudan is 1,304,7000 ha. Approximately 90% of the water abstracted from the Blue Nile in Sudan is used for irrigation, with domestic, industry and other uses accounting for the remaining 10% (World Bank 2000).

TABLE 12. Existing dams in the Blue Nile Catchment.

Dam	River	Location		Storage	Built	Purpose
		Latitude	Longitude	(Mm^3)		
			Ethiopia			
Chara Chara	Abay	11.60	37.38	9,100⁺	2000	Regulation of Lake Tana outflows for hydropower production at Tis Abay I and Tis Abay II power stations (installed capacity - 84MW)
Finchaa*	Finchaa			2,395	1971	Regulation for hydropower production (installed capacity - 134 MW) and also sugarcane irrigation (8,145 ha)
			Sudan			
Roseires	Blue Nile	11.85	34.38	3,024	1964	Regulation for hydropower production (installed capacity - 280 MW) all irrigation schemes (1,305,000 ha)
Sennar	Blue Nile	13.55	33.63	930	1925	Regulation for hydropower production (installed capacity - 15 MW) and supply to Gezira irrigation scheme (882,000 ha)

⁺ this is the active storage of Lake Tana that is controlled by the operation of the weir (i.e., lake levels between 1,784 and 1,787 masl). It represents 2.4 times the average annual outflow of the lake.

* a small dam located on the Amerty River (storage 40 Mm^3) diverts water from the Amerty into the Finchaa Reservoir.

TABLE 13. Existing irrigation schemes in the Sudanese Blue Nile.

Scheme	Command area (ha)	Crops
Gezira and Managil	882,000	Cotton and mixed crops
Rahad	148,000	Mixed crops
El Souky	29,800	Mixed crops
Public pumps	73,500	Mixed crops
Private pumps	58,800	Mixed crops
Al Gnaid	34,900	Sugar
Sugar Northwest Sennar	14,700	Mixed crops
Abu Naama	12,600	Mixed crops
Al Sait, Waha	50,400	Mixed crops
TOTAL	1,304,700	

Source: Ahmed 2006.

5.2. Future Development

5.2.1. Irrigation

The Nile riparian countries have agreed to collaborate in the development of the Nile water resources to achieve sustainable socioeconomic development. There is significant potential for further water resources development in Ethiopia and in downstream countries.

In Ethiopia, possible irrigation projects have been investigated over a number of years (e.g., USBR 1964; WAPCOS 1990; BCEOM 1998). Currently envisaged irrigation projects will cover a total of more than 174,000 ha, which represents 21% of the 815,581 ha of potential irrigation[8] estimated in the basin (BCEOM 1998) (Figure 32). Major irrigation schemes that are currently being planned and/or being implemented are described in Table 14.

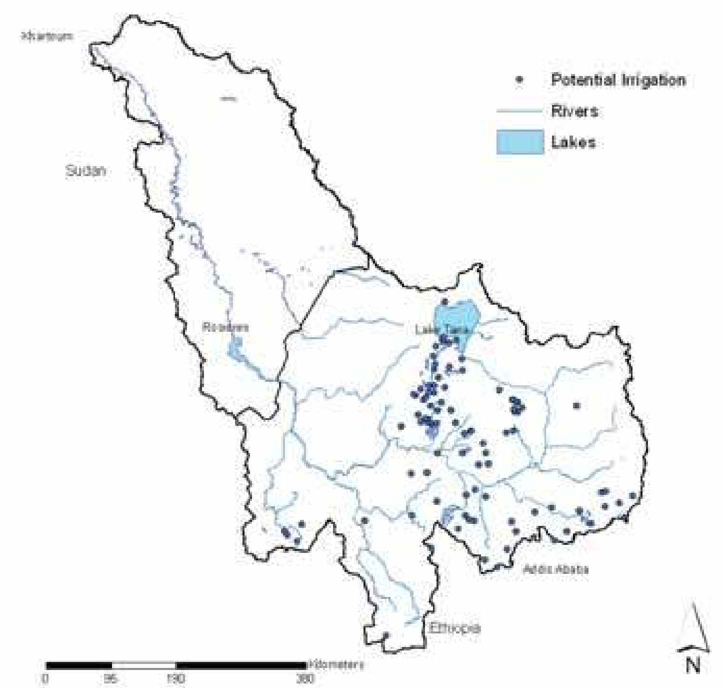


FIGURE 32. Map showing potential sites for future "modern" irrigation schemes in the Ethiopian Blue Nile.

An analysis of the water resources required to support the Ethiopian irrigation development, proposed in the Abay River Master Plan (BCEOM 1998), indicates that approximately 5,750 Mm^3 would be needed to irrigate between 370,000 and 440,000 ha. This represents approximately 12% of the mean annual flow of the Blue Nile from Ethiopia. More recently, it has been estimated that the water required for the 220,416 ha of highest priority irrigation would be between 2,200 and 3,830 Mm^3 (Endale 2006).

Sudan is also planning to increase the area irrigated in the Blue Nile Basin. Additional new projects and extension of existing schemes are anticipated to add an additional 889,340 ha by 2025 (Table 14). Unless irrigation efficiencies are significantly better than those currently achieved in the Gezira and other schemes, this will require approximately 9,000 Mm^3 more water than is abstracted at present, which is about 18.5% of the annual flow of the Blue Nile.

TABLE 14. Major planned irrigation development in the Blue Nile Basin.

Name	Catchment	Command area (ha)	Description	Possible completion date
		Ethiopia		
Angar-Nekemt irrigation project	Angar	26,000	Two dams to be built on the upper reaches of the river	Unknown
Didessa irrigation project	Didessa	55,000	Three dams to be built on the Didessa River and the Dabana and Negeso tributaries	Unknown
Koga irrigation and watershed management project	Koga	7,200	Dam currently being constructed on the Koga River, which flows into Lake Tana	2008
Lake Tana irrigation projects	Lake Tana	50,000	In addition to the Koga scheme, four dams to be constructed on the major rivers flowing into Lake Tana	Unknown
Extension of Finchaa sugarcane scheme	Finchaa	$12,000^{+}$	Extension of existing scheme from the west bank to the east bank of the Finchaa River, using flow regulated by the existing Finchaa Reservoir	Unknown
Beles	Beles	14,000 (-)	Using water diverted from the Tana Catchment, after it has been used for hydropower production	2009
	TOTAL	164,200		
		Sudan		
Rahad	Rahad	$19,740^{+}$	Extension of existing scheme	2025
El Souky		$6,300^{+}$	Extension of existing scheme	2025
Public pumps		$39,900^{+}$	Extension of existing scheme	2025
Private pumps		$4,200^{+}$	Extension of existing scheme	2025
Sugar Northwest				
Sennar		$4,200^{+}$	Extension of existing scheme	2025
Abu Naama		$2,100^{+}$	Extension of existing scheme	2025
Al Sait, Waha		$50,410^{+}$	Extension of existing scheme	2025
Kenana II and II		420,100		2025
Rahad II	Rahad	210,000		2025
South Dinder	Dinder	132,000		2025
	TOTAL	888,950		

$^{+}$ additional areas (i.e., to be added to existing schemes),
- This represents just 10% of the identified economical feasible potential
Source: various

5.2.2. Hydropower

In the Ethiopian Blue Nile more than 120 potential hydropower sites have been identified within the Blue Nile reach (WAPCOS 1990). Of these 26 sites were investigated in detail during the preparation of the Abay River Basin Master Plan (BCEOM 1998) (Figure 33). The major hydropower projects currently being contemplated in Ethiopia have a combined installed capacity of between 3,634 and 7,629 MW (Table 15). The exact figure depends on the final design of the dams and the consequent head that is produced at each site. The four largest schemes being considered are dams on the main stem of the Blue Nile River. Of these schemes the one that has advanced the furthest is the Karadobi project for which the pre-feasibility study was conducted in 2006 (Norconsult 2006).

In addition to the schemes listed in Table 14, it is anticipated that power generation will be added to several of the proposed irrigation projects where dams are being built. It is estimated that this could provide an additional 216 MW of capacity (BCEOM 1998). The possible total annual energy produced by all the hydropower schemes being considered is in the range 16,000–33,000 GWh. This represents 20-40% of the technical potential in the Ethiopian Blue Nile (i.e., 72,000 GWhyr^{-1}) estimated by the Ministry of Water Resources. Currently, it is anticipated that much of the electricity generated by these power stations will be sold to Sudan and possibly Egypt.

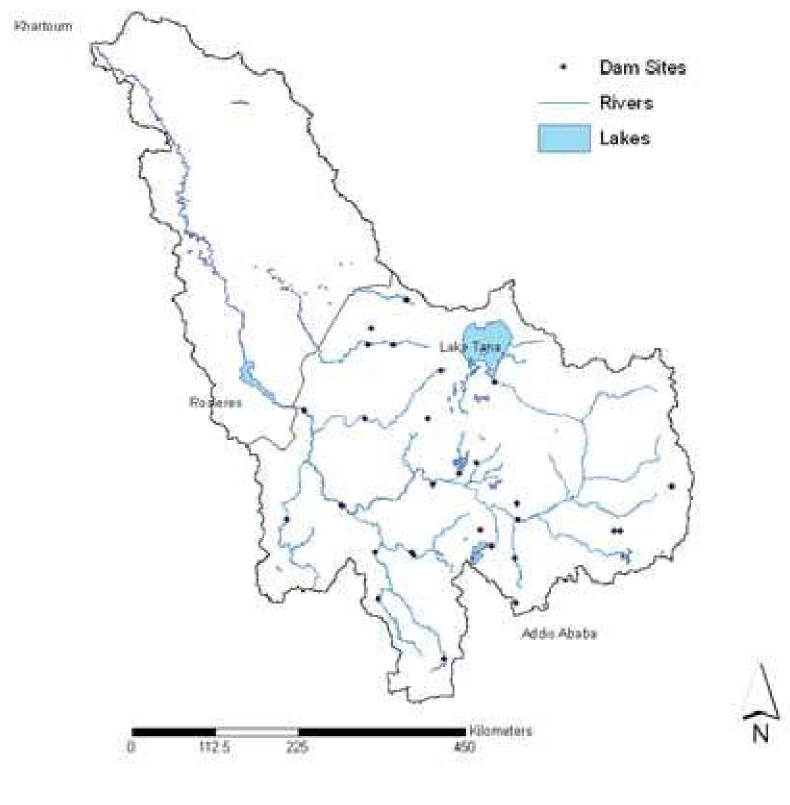


FIGURE 33. Map showing the location of potential hydropower sites in the Ethiopian Blue Nile, investigated in the development of the Abay River Basin Master Plan (*Source:* BCEOM 1998).

TABLE 15. Major planned hydropower schemes in the Ethiopian Blue Nile Basin.

Name	Catchment	Location		Description	Anticipated capacity (MW)[+]	Energy (GWh)	Possible completion date
		Latitude	Longitude				
Karadobi	Blue Nile	9.86	37.69	250 m high concrete dam. Total reservoir volume 40,220 Mm^3. Live volume 17,300 Mm^3. Full supply level 1,146 masl. Reservoir area 460 $km^{2\#}$	660–1,580	2,890-6,920	Unknown
Mabil	Blue Nile	10.32	36.67	170 m high dam. Total reservoir volume 13,600 Mm^3. Full supply level*	510–1,400	2,230-6,130	Unknown
Mendaia	Blue Nile	10.07	36.57	164 m high dam. Total reservoir volume 15,900 Mm^{3*}	980–1,700	4,290-6,750	Unknown
Border	Blue Nile	11.21	35.09	84.5 m high dam. Total reservoir volume 11,100 Mm^{3*}	750–1,780	3,285-7,800	Unknown
Beles Dangur	Beles	11.11	35.84		104–143	455-626	2009
Fettam	Fettam	10.45	37.01		94–139	410-608	Unknown
Lower Didessa	Didessa	9.48	35.98		190–400	832-1,752	Unknown
Lower Guder	Guder	9.42	37.66		30–82	131-359	Unknown
Lower Dabus	Dabus	9.96	34.91		164–212	709-928	Unknown
Upper Dabus	Dabus	9.83	34.87		152–193	666-845	Unknown

[+] where a range is indicated the actual value will depend on the final height of the dam and hence the reservoir elevation
[#] Description from feasibility study (Norconsult 2006)
* Description from Block 2007
Source: BCEOM 1998

Technically feasible hydropower energy production in the Nile Basin of Sudan is estimated to be 45,000 GWh per year. However, the majority of this is on the main Nile downstream of the White and Blue Nile confluence and on the Atbara River. Currently, the Merowe Dam, with an installed capacity of 1,250 MW, is being constructed on the main Nile downstream of Khartoum. Several other major dams are being planned. However, currently there are no plans to develop additional hydropower schemes on the Blue Nile and its tributaries.

5.3. Past Modeling of the Water Resources of the Blue Nile

Over the years a number of computer models have been developed to assess and weigh the benefits and impacts of water development and management strategies in the Blue Nile. In the 1980s a multi-objective programming model was developed to investigate the impact of proposed water resources development in the Ethiopian Blue Nile on flows in Sudan and Egypt. This included an evaluation of the four dams proposed for the main stem of the river as well as several irrigation projects. Although based on a number of simplifying assumptions, the study (Guariso and Whittington 1987) concluded that:

- If Ethiopia was to fully develop the Blue Nile Basin for both hydropower and irrigation (with an estimated 6,000 Mm^3 being used in Ethiopia), through better watershed management and efficient utilization of the green water, the overall amount of water available for agricultural use in Sudan and Egypt would increase. Since the river could be regulated more easily downstream with almost constant flow throughout the year, this reduces evaporation losses from all the downstream reservoirs and in particular the Aswan High Dam in Egypt. The Authors of this Working Paper believe that such well recognized and pronounced benefits will enhance the cooperation between these countries (Ethiopia, Sudan and Egypt).
- There is little, if any, conflict between the riparian states on the broad policy of how reservoirs in Ethiopia should be operated.
- Proposed development of irrigation on the Ethiopian portions of the Dinder and Rahad rivers would significantly impact downstream users and does conflict with Sudanese development plans.

More recently, the NileSim model has been developed to simulate water resources of the entire Nile Basin. This model was developed primarily as a learning tool to explain complex river behavior and management to non-technical people. It enables the development of scenarios to examine the effects of policy options and changes caused by manipulating dams and regulating river use (Levy and Baecher 2006).

The Investment Model for Planning Ethiopian Nile Development (IMPEND) has been developed and used to simulate the operation of the four large dams that Ethiopia is considering constructing on the main stem of the Blue Nile (Block 2006; Block 2007). Although necessarily based on many assumptions (including that agreement on water impoundment and abstraction is reached with Sudan and Egypt) the model indicates that, for various scenarios (including potential future climatic conditions and differing flow policies), this large-scale development typically produces cost-benefit ratios from 1.2-1.8 (Block 2007).

To date, perhaps the most comprehensive water resource simulation model developed for the whole of the Nile Basin is the Nile Basin Decision Support Tool. This was developed under the auspices of the Food and Agriculture Organization of the United Nations (FAO) and includes a river and reservoir simulation and management module. This module comprises five components: a) river network configuration; b) river hydrology; c) existing and planned hydropower facilities; d) water use; and e) reservoir operating rules. River and reservoir routing models simulate the movement of water through river reaches, quantifying transmission losses and time lags. Reservoir and lake outflows through hydropower facilities and spillways are modeled with sufficient detail for use in managing operations. An optimizing routine enables dam operating rules to be developed that takes into account the complexity and uncertainty of the system. The module can be used to simulate the impacts of alternative water resources development options (Georgakakos 2006).

5.4. Proposed Modeling Strategy for this Project

Pressure on water resources in the Blue Nile Basin is likely to increase dramatically in the near future as a result of high population growth in all the riparian states, and increasing development-related water needs in Ethiopia and Sudan. However, in spite of the national and international importance of the region, relatively few studies have been conducted and there is only a limited understanding of the basin's detailed climatic, hydrological, topographic and hydraulic characteristics (Johnson and Curtis 1994; Conway 1997).

In the current study a water demand and supply model will be used to ascertain the resource implications of proposed development in Ethiopia and Sudan. The model will be used to gain an insight into the potential downstream consequences of the development of physical infrastructure and water abstractions in a number of different future scenarios. Each scenario will provide a consistent and plausible description of possible future water demand and supply in the catchment. The objective of the water demand and supply modeling is to:

- Simulate water demand and supply for major production activities (existing and planned) in the Blue Nile Basin; and
- Assess the impacts of upstream watershed management and allocation on downstream users.

It has been proposed to configure the model to simulate the 16 principal sub-basin's tributaries identified by various previous studies of water resources in the catchment (Figure 34).

Following a review of available models, the model that was primarily selected for this component of the study is the HEC-ResSim model developed by the US Army Corps of Engineers (US Army Corps of Engineers 2003). The model is designed to be used to evaluate planning and management issues associated with water resources development. The model was selected for this study because: i) it is relatively simple to use, ii) it can work with the relatively limited data available, and iii) it can simulate the operation of hydraulic structures.

The HEC-ResSim model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. The elements that comprise the water demand-supply system and their spatial relationship are characterized within the model. The system is represented in terms of its various water sources, withdrawal and transmission networks (including reservoirs) as well as different water demands and supplies.

In the current study the model will be set up to use available flow data as input (i.e., it will not be used to simulate natural hydrological processes). The model will initially be configured to simulate the current conditions within the catchment. The water availability and demand for this can be reasonably and confidently determined using available abstraction data for irrigation schemes in Sudan. This will provide a "baseline" against which the future scenarios can be compared. The model simulation will be validated by comparing the flow accumulated from sub-basins situated upstream of the main stem gauges located at:

i) Lake Tana outlet,
ii) Kessie,
iii) the border, and
iv) Khartoum

The model will then be used to simulate the alternative future scenarios to assess the impact of different development and management options. Data for the future scenarios will largely be obtained from the Abay Basin Master Plan in Ethiopia and, where available, from project specific reports (e.g., feasibility studies). Model simulation will be done on a monthly time-step.

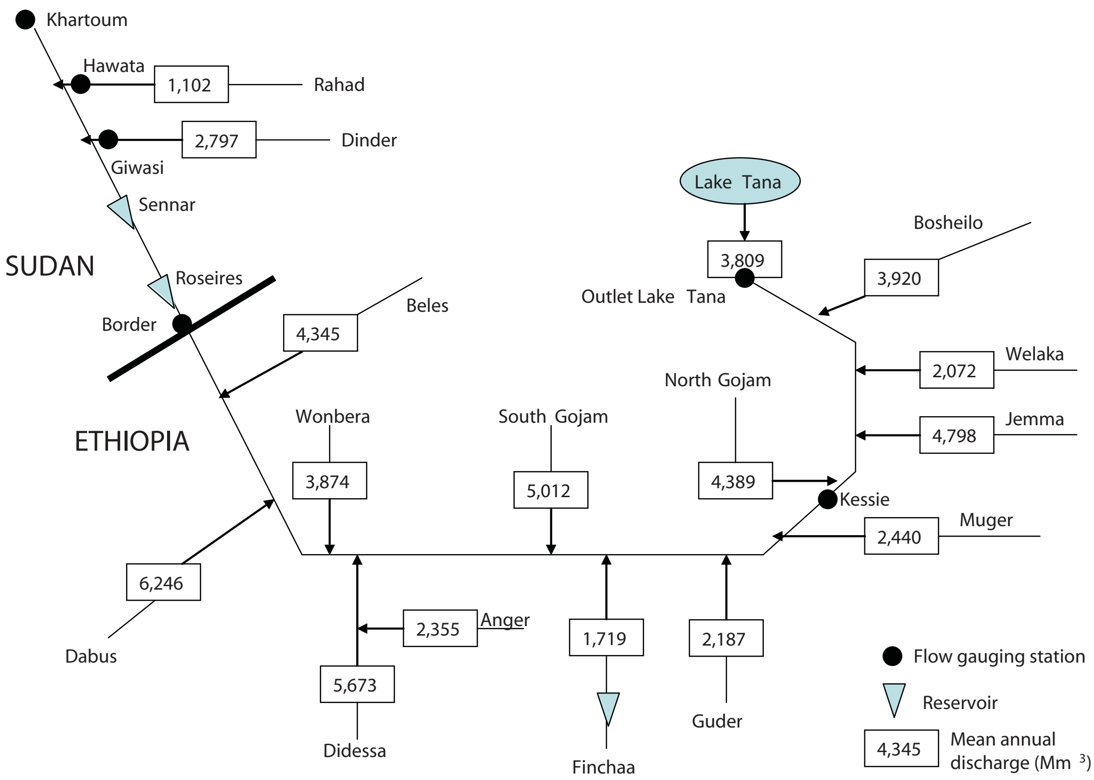


FIGURE 34. Schematic showing the proposed configuration of the water demand and supply model to be used in this study. Mean annual discharge figures from Tesfahun et al. (2006).

6. DISCUSSION/RECOMMENDATIONS

The purpose, rationale and aims of the project entitled "Improved water and land management in the Ethiopian Highlands and its impact on downstream stakeholders dependent on the Blue Nile" have been provided. The project is intended to answer key questions such as:

- what are successful interventions that can improve agricultural productivity and simultaneously reverse degradation?
- what are the likely downstream impacts of these interventions?
- what are the opportunities for enhancing rural livelihoods and food security?

The research will address these questions and provide insight into the existing situation. The review reported here has identified gaps in knowledge and outlined the research methodologies and approaches to be used in the project.

The coverage of data in the basin is highly variable and generally very scarce. Hence:

- A considerable area of the Blue Nile River Basin is un-gauged. As an example, about 40% of the Lake Tana sub-basin is un-gaugged. Most gauges are located either in the headwaters or close to the middle of the watersheds, with very few located close to the confluence with the main river.
- High resolution (i.e., daily) meteorological data covering many parameters (i.e., class 1 stations) are very rare.

- Sediment data are very scarce. There is no continuous sediment monitoring station in the Abay part of the basin. There is, however, better data and information on the main stem of the Blue Nile, at reservoirs in Sudan.

The hydrology of the Basin has been described. Many models developed in temperate climates do not simulate runoff well in Ethiopia. Analyses of rainfall and runoff data indicate that saturation excess, rather than infiltration excess, is the dominant mechanism for runoff generation. As a result, simple water balance approaches, based on the limited data available, simulate flows reasonably well. In the current study, the SWAT model has been modified and will be used to simulate flow at a range of scales, from small watersheds up to the scale of the main tributaries. In addition, a number of rainfall-runoff models will be tested.

Modeling of sediment and evaluation of possible watershed management interventions has been conceptualized and will be conducted using a nested approach. The various scales that will be considered are: micro-watershed with outlets at streams (e.g., SCRP sites); watersheds with outlets to small dams (e.g., Koga Dam); sub-basin with outlets to the main stem of the Blue Nile or Lake Tana; Abay Outlet at El Deim and downstream in irrigation canals. Erosion, sediment yield and rainfall-runoff mechanisms will be studied at SCRP sites to establish fundamental relationships. Such analyses combined with other measured data will establish sediment magnitude at key small dam locations. By establishing watershed parameters related to discharge, area and land-use, sediment input to the main river will be estimated and discharge-sediment relationships at the outlet to the basin will be established for the major outlets. The sediment budget of the major reservoirs and sediment trapping efficiency will be used to establish the sediment loads downstream of the reservoirs and provide a baseline against which to assess the impact of upstream interventions.

The current use of water resources and the future potential of the basin have been described. This information provides a baseline from which to carryout analysis of existing water use and demand and supply as well as analyses of future scenarios. In the short and medium term, there is considerable demand and supply for power production and irrigation development (up to 200,000 ha) in Ethiopia. Currently, there is no envisaged hydropower development in the Sudanese part of the Blue Nile except the heightening of the Roseires Dam which is going to increase its capacity by 4.000 Mm^3. However, detailed analyses are required to assess the impact of proposed irrigation development in the Sudanese part of the basin. In order to fully understand the impacts of planned developments, different scenarios will be assessed using the HEC-ResSim model.

It is hoped that the vast list of references, the descriptions of previous models used in the basin and the lists of hydrological, meteorological and sediment measuring stations compiled in this report will be useful for other researchers conducting studies in the basin. It is anticipated that this study will provide information, knowledge and important insights into water management options in the Blue Nile Basin which will be reported in future reports.

7. APPENDICES

7.1. Appendix 1. List of Meteorological Data Stations in Abay-Blue Nile

a. Ethiopia

SNO	Sub-basin	Station Name	STN_ID	B_DATE	LATITUDE	LONGITUDE	ALT	CLASS	TOTAL_MARF
1	ANGER	Alibo	37090063	1968	9.9	37.06667	2300	3	1,336.5
2	BESHILO	Tenta Tate	39110024	1955	11.33333	39.23333	2060	4	749
3	BESHILO	Wegel Tena	39110141	1978	11.6	39.21667	3000	1	722
4	DABUS	Bambasi	34090033	1972	9.71667	34.71667	1460	3	1,300.1
5	DABUS	Begi	34090083	1967	9.33333	34.53333	1650	3	1,294.1
6	DABUS	Guliso	35090063	1978	9.2	35.51667	1600	3	1,429
7	DABUS	Hena	35090043	1973	9.45	35.6	1700	3	1,345
8	DABUS	Hor Kelifa	34100014	1974	10.63333	34.93333	200	4	1,424
9	DABUS	Jarso	35090084	1980	9.45	35.31667	1750	4	1,374
10	DABUS	Kiltu Kara	35090044	0	9.71667	35.21667	1850	4	1,270
11	DABUS	Mendi	35090013	1955	9.78333	35.1	1650	3	1,766
12	ANGER	Anger Guti	36090031	1959	9.26667	36.33333	1350	1	1,367.1
13	DABUS	Menge	34100034	1975	10.33333	34.73333	1200	4	1,313
14	DABUS	Nejo	35090111	1981	9.5	35.45	1800	1	1,601
15	DIDESSA	Abdella	36080214	1982	8.36667	36.25	2010	4	2,022.7
16	DIDESSA	Agaro	36070483	1952	7.85	36.6	2030	3	1,471.3
17	DIDESSA	Bereda (SF)	36090103	1979	9.16667	36.33333	1390	3	1,633.7
18	DIDESSA	Chora	36080013	1950	8.35	36.11667	2090	3	1,717.8
19	DIDESSA	Dembi	36080414	1954	8.06667	36.45	1950	4	2,012.6
20	DIDESSA	Dengoro	35090101	1980	9.2	35.73333	1900	1	2,092.9
21	DIDESSA	Dedesa (SF)	36090061	1972	9.38333	36.1	1200	1	1,477.1
22	DIDESSA	Gechi	36080054	1957	8.33333	36.41667	2130	4	1,846
23	ANGER	Gidayana	36090301	1958	9.86667	36.93333	1850	1	1,709
24	DIDESSA	Gimbi	35090261	1978	9.16667	35.78333	1970	1	1,618
25	DIDESSA	Nekemte	36090011	0	9.08333	36.45	2080	1	2,002

(continued...)

7.1. Appendix 1. List of Meteorological Data Stations in Abay-Blue Nile (continued ...)

SNO	Sub-basin	Station Name	STN_ID	B_DATE	LATITUDE	LONGITUDE	ALT	CLASS	TOTAL_MARF
26	DIDESSA	Nole kaba	35080233	1982	8.95	35.83333	1800	3	1,952
27	DIDESSA	Sibu Sire	36090123	1984	9.03333	36.85	1750	3	1,359
28	FINCHAA	Finchaa	37090121	1979	9.56667	37.36667	2320	1	1,248
29	FINCHAA	Hareto	37090133	1982	9.35	37.11667	2260	3	1,771
30	FINCHAA	Kombolcha	37090043	1958	9.6	37.5	2100	3	1,393
31	FINCHAA	Neshi	37090301	1969	9.65	37.2	2500	1	1,334
32	FINCHAA	Shambo	37090311	1850	9.56667	37.1	2430	1	1,849
33	GUDER	Asgori	38080283	1980	8.96667	38	2500	3	1,056.7
34	BELES	Dangela	36110011	1954	11.11667	36.41667	1290	1	1,480.3
35	GUDER	Gedo	37090404	1954	9.05	37.43333	2500	4	1,211
36	GUDER	Tikur Inch	37080031	1955	8.78333	37.63333	2480	1	1,516
37	JEMMA	Chacha	39090024	1954	9.55	39.45	0	4	923.9
38	JEMMA	Dabena	39090194	1850	9.76667	39.2	2600	4	1,764.9
39	JEMMA	Debre Birh	39090151	1980	9.63333	39.5	2750	1	891.4
40	JEMMA	Fiche	38090021	1954	9.8	38.7	2750	1	974
41	JEMMA	Gebre Gura	38090201	1980	9.81667	38.41667	2560	1	1,270
42	JEMMA	Ghoha Tsio	38100023	1955	10.03333	38.23333	2550	3	1,107
43	JEMMA	Guder	39080334	1960	8.95	39.78333	2002	4	1,361
44	JEMMA	Jihur	39100434	1991	10.03333	39.25	0	4	1,470
45	BELES	Mandura	36110023	1972	11.11667	36.41667	1290	3	1,961
46	JEMMA	Jimmadogol	39100143	1980	10.43333	39.25	2550	3	1,668
47	JEMMA	Lemi	38090153	1973	9.81667	38.9	2500	3	1,159
48	JEMMA	Molale	39100034	1955	10.11667	39.65	3000	4	821
49	JEMMA	Miker turi	38090643	1989	9.55	38.86667	1979	3	1,012
50	JEMMA	Sela dinga	39090064	1955	9.95	39.61667	2870	4	975
51	JEMMA	Sheno	39090141	1989	9.33333	39.3	2655	1	987
52	MUGER	Chancho	39090424	1972	9.31667	38.75	0	4	1,192.1
53	MUGER	Derba	38090163	1974	9.43333	38.63333	2350	3	1,302.7
54	MUGER	Shekute	38090214	1980	9.43333	38.05	2560	4	1,647
55	MUGER	Sholla geb	38090544	1962	9.05	38.76667	2500	4	981

(continued...)

7.1. Appendix 1. List of Meteorological Data Stations in Abay-Blue Nile (continued ...)

SNO	Sub-basin	Station Name	STN_ID	B_DATE	LATITUDE	LONGITUDE	ALT	CLASS	TOTAL_MARF
56	BESHILO	Dessie	39110044	1956	11.1	39.63333	2500	4	1,136.5
57	MUGER	Sululta	38090083	1961	9.18333	38.73333	2610	3	1,127
58	NORTH GOJAM	Debre Work	38100113	1975	10.73333	38.13333	2740	3	951.1
59	NORTH GOJAM	Dejen	38100034	1957	10.16667	38.15	2420	4	1,146.9
60	NORTH GOJAM	Felege Bir	38100274	1979	10.75	38.06667	2680	4	1,348
61	NORTH GOJAM	Gundo Woin	38100124	1979	10.93333	38.08333	2700	4	1,518
62	NORTH GOJAM	Mota	37110361	1961	11.08333	37.86667	2440	1	1,147
63	NORTH GOJAM	Tis Abay	37110174	1983	11.5	37.58333	1620	4	1,145
64	NORTH GOJAM	Yetmen	38100303	1974	10.33333	38.13333	2060	3	1,249
65	REHAD	Metema	36120011	1850	12.96667	36.16667	900	1	932
66	SOUTH GOJAM	Chagni	36100221	1850	10.95	36.5	1620	1	1,703.9
67	BESHILO	Kuta Ber	39110034	1956	11.26667	39.53333	2700	4	1,067
68	SOUTH GOJAM	Debre Mark	37100402	1953	10.33333	37.66667	2515	2	1,333.7
69	SOUTH GOJAM	Dibate	36100034	1980	10.65	36.55	1600	4	1,070.6
70	SOUTH GOJAM	Elias	37100093	1980	10.3	37.46667	2140	3	1,479.6
71	SOUTH GOJAM	Enjabar	36100054	1981	10.96667	36.9	2670	4	2,124
72	SOUTH GOJAM	Filklik	38100083	1972	10.05	38.16667	1850	3	1,020
73	SOUTH GOJAM	Finote Sel	37100051	1968	10.68333	37.26667	1900	1	1,035
74	SOUTH GOJAM	Jiga	37100061	1970	10.66667	37.36667	1980	1	1,411
75	SOUTH GOJAM	Lumame	37100123	1981	10.25	37.93333	2550	3	1,134
76	SOUTH GOJAM	Tilili	37100111	1980	10.85	37.05	2570	1	1,943
77	TANA	Addis Zeme	37120113	1974	12.11667	37.86667	1550	3	1,353.9
78	BESHILO	Nefas mewc	38110163	1957	11.73333	38.45	3000	3	1,105
79	TANA	Ambagiorgi	37120204	1954	12.76667	37.6	2900	4	815.1
80	TANA	Bahir Dar	37110071	1961	11.6	37.4	1770	1	1,451.2
81	TANA	Debe Tabor	38110011	1951	11.88333	38.03333	2690	1	1,569.2
82	TANA	Dek Istifa	37110054	1960	11.9	37.26667	1795	4	1,900.1
83	TANA	Delgi	37120103	1974	12.23333	37.03333	1800	3	718.3
84	TANA	Enfraz	37120123	1977	12.18333	37.68333	1500	3	1,181.6
85	TANA	Gondar	37120011	1952	12.55	37.41667	1967	1	1,057

(continued...)

7.1. Appendix 1: List of Meteorological Data Stations in Abay-Blue Nile (continued ...)

SNO	Sub-basin	Station Name	STN_ID	B_DATE	LATITUDE	LONGITUDE	ALT	CLASS	TOTAL_MARF
86	TANA	Gorgora	37120221	1972	12.25	37.3	1830	1	926
87	TANA	Gumera	37110143	1978	11.83333	37.63333	1880	3	1,039
88	TANA	Maksegnit	37120073	1970	12.36667	37.55	1450	3	967
89	BESHILO	Sirinka	39110211	1980	11.55	39.61667	2000	1	923
90	TANA	Merawi	37110083	1967	11.41667	37.15	2110	3	1,572
91	TANA	Wereta	37110374	1980	11.91667	37.68333	1980	4	1,237
92	TANA	Yifag	37020131	1978	12.06667	37.71667	1200	1	1,007
93	TANA	Zege	37110123	1974	11.68333	37.31667	1800	3	1,391
94	WONBERA	Haro	36090043	1970	9.9	36.45	2200	3	1,161

b. Sudan

Station ID	Station name	Start date	End date	Dt (Days)	No. of years	% missing
80003	DONGOLA	01-Jan-45	30-Sep-06	1	62	9.8
80006	KARIMA	01-Jan-36	30-Sep-06	1	71	8.6
80009	WADI HALFA	01-Apr-43	30-Sep-06	1	64	21.2
80010	ABU HAMED	01-Jan-09	31-Aug-06	1	98	7.2
80011	ATBARA	01-Jan-08	30-Sep-06	1	99	7.2
80012	HUDEIBA	09-Oct-68	30-Sep-06	1	38	15.9
80013	SHENDI	01-Jan-41	30-Sep-06	1	66	10.6
80021	PORT SUDAN	04-Jan-42	30-Sep-06	1	65	10.9
80034	KHARTOUM	01-Jan-01	30-Sep-06	1	106	7.1
80037	SHAMBAT	01-Jan-13	30-Sep-06	1	94	10.7
80042	EL GEDARIF	01-Jan-04	30-Sep-06	1	103	9.8
80044	HALFA EL GADEEDA	14-Jul-70	30-Sep-06	1	36	16.7
80046	KASSALA	01-Feb-07	30-Sep-06	1	100	8.1
80076	HASAHEISA	01-Jan-93	30-Sep-06	1	14	43.6
80192	EN NAHUD	01-Jan-12	30-Sep-06	1	95	6.7

(continued...)

7.1. Appendix 1: List of Meteorological Data Stations in Abay-Blue Nile (continued ...)

Station ID	Station name	Start date	End date	Dt (Days)	No. of years	% missing
80193	EL OBEID	01-Jan-43	30-Sep-06	1	64	11.5
80200	EL FASHER	01-Nov-42	30-Sep-06	1	64	12.6
80201	EL GENEINA	01-Jan-28	30-Sep-06	1	79	8.0
80224	NYALA	01-Jan-20	30-Sep-06	1	87	7.9
80241	KADUGLI	01-Jan-12	30-Sep-06	1	95	9.8
80245	RASHAD	01-Jan-16	30-Sep-06	1	91	6.7
80249	ABU NAAMA	01-Jan-64	29-Sep-06	1	43	15.0
80252	ED DAMAZIN	01-Jul-62	31-Jul-06	1	44	13.7
80265	SENNAR	01-Jan-65	30-Sep-06	1	42	14.7
80271	UMM BENEIN	01-Sep-59	30-Sep-06	1	47	20.1
80274	KODOK	01-Jan-03	31-Jul-78	1	76	4.1
80275	MALAKAL	01-Jan-40	30-Sep-06	1	67	9.5
80280	EL RENK	01-Jan-06	31-Aug-06	1	101	7.8
80287	RAGA	20-Jun-07	31-Jan-06	1	99	11.9
80298	JUBA	01-Jan-49	30-Sep-06	1	58	10.6
80321	SAHAFA POLICE	01-Jan-75	30-Sep-06	1	32	28.3
80323	OMDURMAN (ELTHAWRA)	01-Jan-93	30-Sep-06	1	14	52.2
80324	TOTI ISLAND	01-Jan-93	30-Sep-06	1	14	43.6
80337	ABU KU	01-Jan-93	30-Sep-06	1	14	49.7
80236	BABANUSA	01-Jun-74	31-Aug-06	1	32	20.6

7.2. Appendix 2: List of Hydrological Stations in Blue Nile

a. Ethiopia

S_NO	MAIN_CATCH	SUB_CATCH	STATION_NO	RIVER_LAKE	SITE	LATITUDE	LONGITUDE
1	Abay	Dabus(5)	115001	Dabus	U. S. Abbay Conf	10.61667	35.15
2	Abay	Dabus(5)	115002	Dabus	Nr. Assosa	9.86667	34.9
3	Abay	Dabus(5)	115003	Hoha	Nr. Assosa	10.15	34.63333
4	Abay	Dabus(5)	115004	Hujur	Nr. Nedjo	9.63333	35.33333
5	Abay	Dabus(5)	115005	Haffa	Nr. Assosa	9.96667	34.66667
6	Abay	Dabus(5)	115006	Sechi	Nr. Mendi	9.7	35.21667
7	Abay	Dabus(5)	115007	Gambella	Nr. Assosa	10	34.61667
8	Abay	Dabus(5)	115008	Aleltu	at Nedjo	9.5	35
9	Abay	Dabus(5)	115009	Dilla	Nr. Nedjo	9.45	35.55
10	Abay	Dabus(5)	115010	Komis	Nr. Gori	9.56667	35.38333
11	Abay	Dabus(5)	115011	Mutsa	Nr. Bambasi	9.75	34.73333
12	Abay	Dabus(5)	115012	Tigi	Nr. Bambasi	9.75	34.73333
13	Abay	Dabus(5)	115013	Songa	Nr. Bambasi	9.75	34.73333
14	Abay	Didessa-A-4	114001	Sisessa	Nr. Arjo	8.68333	36.41667
15	Abay	Didessa-A-4	114002	Anger	Nr. Nekemte	9.43333	36.51667
16	Abay	Didessa-A-4	114003	Sifa	Nr. Nekemte	8.86667	36.78333
17	Abay	Didessa-A-4	114004	Wama	Nr. Nekemte	8.78333	36.78333
18	Abay	Didessa-A-4	114005	Dabana	Nr. Abasina	9.03333	36.05
19	Abay	Didessa-A-4	114006	Uke	Nr. Nekemte	9.31667	36.51667
20	Abay	Didessa-A-4	114007	Little Ang	at Angar Gutin	9.5	36.58333
21	Abay	Didessa-A-4	114008	Yebu	at Yebu	7.8	36.7
22	Abay	Didessa-A-4	114009	Urgessa	Nr. Gembe	7.83333	36.65
23	Abay	Didessa-A-4	114010	Tato	Nr. Gutie	9.03333	36.65
24	Abay	Didessa-A-4	114011	Meka	Nr. Nekemte	9.05	36.3
25	Abay	Didessa-A-4	114012	Idris	Nr. Sire	9.03333	36.85
26	Abay	Didessa-A-4	114013	Dabana	Nr. Bunobedele	8.4	36.28333
27	Abay	Didessa-A-4	114014	Didessa	Nr. Dembi	8.05	36.45
28	Abay	Didessa-A-4	114015	Chereti	Nr. Army Camp	8.91667	36.36667

(continued...)

7.2. Appendix 2: List of Hydrological Stations in Blue Nile (continued ...)

S_NO	MAIN_CATCH	SUB_CATCH	STATION_NO	RIVER_LAKE	SITE	LATITUDE	LONGITUDE
29	Abay	Didessa-A-4	114016	Loko	at Agro Industria	9.36667	36.6
30	Abay	Didessa-A-4	114017	Haro	at Agro Industria	9.4	36.66667
31	Abay	Didessa-A-4	114018	Uke	Nr. Nekemte	9.31667	36.51667
32	Abay	Didessa-A-4	114019	Temsa	Nr. Agaro	7.85	36.58333
33	Abay	Dinder (7)	117001	Dinder	Nr. Abu Mendi	12.05	36.08333
34	Abay	Lake Tana 1	111001	Lake Tana	at Bahir Dar	11.6	36.38333
35	Abay	Lake Tana 1	111002	Gelgel A.	Nr. Marawi	11.36667	37.03333
36	Abay	Lake Tana 1	111003	Koga	at Merawi	11.36667	37.05
37	Abay	Lake Tana 1	111004	Lake Tana	at Gorgora	12.23333	37.3
38	Abay	Lake Tana 1	111005	Ribb	Nr. Addis Zemen	12	37.71667
39	Abay	Lake Tana 1	111006	Gumera	Nr. Bahir Dar	11.83333	37.63333
40	Abay	Lake Tana 1	111007	Megech	Nr. Azezo	12.48333	37.45
41	Abay	Lake Tana 1	111008	Dek Stefan	at Lake Tana	11.9	37.26667
42	Abay	Lake Tana 1	111009	Upper Ribb	on D. Tabor Road	12.05	37.98333
43	Abay	Lake Tana 1	111010	Angreb	Nr. Gondor	12.63333	37.48333
44	Abay	Lake Tana 1	111011	Lake Tana	Lake Tana	11.9	37
45	Abay	Lake Tana 1	111012	Sheni	at Addis Zemen	12.11667	37.78333
46	Abay	Lake Tana 1	111013	Zufil	Nr. Tabor	11.83333	38.08333
47	Abay	Lake Tana 1	111014	Gelda	Nr. Ambessame	11.7	37.63333
48	Abay	Lake Tana 1	111015	Ribb	Nr. Gasai	11.8	38.15
49	Abay	Lake Tana 1	111016	Gemero	Nr. Maksegnit	12.38333	37.55
50	Abay	Lake Tana 1	111017	Fegoda	Nr. Arb Gebeya	11.63333	37.76667
51	Abay	Lake Tana 1	111018	Garno	Nr. Infranz	12.23333	37.61667
52	Abay	Lake Tana 1	111019	Ezana	Nr. Bahir Dar	11.48333	37.4
53	Abay	Lake Tana 1	111020	Bered	at Merawi	11.41667	37.16667
54	Abay	Lake Tana 1	111021	Amen	at Dangila	11.26667	36.86667
55	Abay	Lower Abay (6)	116001	Abbay	at Shegolie	10.65	35.15
56	Abay	Lower Abay (6)	116002	Abbay	at Sudan Border	11.23333	34.98333
57	Abay	Lower Abay (6)	116003	Beles	Nr. Pawi (Metekel)	11.2	36.33333
58	Abay	Lower Abay (6)	116004	Gilgel Be.	Nr. Mandura	11.16667	36.36667
59	Abay	Lower Abay (6)	116005	Main Beles	at Bridge	11.25	36.45
60	Abay	Middle N. 3	113001	Bello	Nr. Guder	8.86667	37.66667

(continued...)

7.2. Appendix 2: List of Hydrological Stations in Blue Nile (continued ...)

S_NO	MAIN_CATCH	SUB_CATCH	STATION_NO	RIVER_LAKE	SITE	LATITUDE	LONGITUDE
61	Abay	Middle N. 3	113002	Fatto	Nr. Guder	8.86667	37.71667
62	Abay	Middle N. 3	113003	Gibat	Nr. Guder	8.85	37.75
63	Abay	Middle N. 3	113004	Melke	Nr. Guder	8.85	37.73333
64	Abay	Middle N. 3	113005	Guder	at Guder	8.95	37.75
65	Abay	Middle N. 3	113006	Indris	at Guder	8.93333	37.75
66	Abay	Middle N. 3	113007	Finchaa	Nr. Shambo	9.55	37.38333
67	Abay	Middle N. 3	113008	Chemoga	Nr. Debre Markos	10.3	37.73333
68	Abay	Middle N. 3	113009	Digil	Nr. Debre Markos	10.35	37.66667
69	Abay	Middle N. 3	113010	Kulech	Nr. Debre Markos	10.36667	37.61667
70	Abay	Middle N. 3	113011	Jedeb	Nr. Ama Nuel	10.4	37.56667
71	Abay	Middle N. 3	113012	Gudla	at Dembecha	10.55	37.5
72	Abay	Middle N. 3	113013	Birr	Nr. Jiga	10.65	37.38333
73	Abay	Middle N. 3	113014	Temcha	Nr. Dembecha	10.53333	37.5
74	Abay	Middle N. 3	113015	Leza	Nr. Jiga	10.66667	37.33333
75	Abay	Middle N. 3	113016	Arara	Nr. Finote Selam	10.68333	37.25
76	Abay	Middle N. 3	113017	Lah	Nr. Finote Selam	10.68333	37.26667
77	Abay	Middle N. 3	113018	Selala	Nr. Bure	10.7	37.11667
78	Abay	Middle N. 3	113019	Fettam	at Tilile	10.85	37.01667
79	Abay	Middle N. 3	113020	Debohila	Nr. Bure	10.7	37.16667
80	Abay	Middle N. 3	113021	Ketchem	Nr. Jiga	10.63333	37.41667
81	Abay	Middle N. 3	113022	Temim	Nr. Finote Selam	10.66667	37.31667
82	Abay	Middle N. 3	113023	Dura	Nr. Metekel	10.98333	36.48333
83	Abay	Middle N. 3	113024	Guder	at Abbay Conf	9.85	37.66667
84	Abay	Middle N. 3	113025	Abbay	D.S. Guder Confl	9.86667	37.66667
85	Abay	Middle N. 3	113026	Neshi	Nr. Shambo	9.75	37.25
86	Abay	Middle N. 3	113027	Amerti	Nr. Shambo	9.73333	37.28333
87	Abay	Middle N. 3	113028	Dondor	Nr. Metekel	10.93333	36.51667
88	Abay	Middle N. 3	113029	Ardy	Nr. Metekel	10.95	36.51667
89	Abay	Middle N. 3	113030	Upper Che.	Nr. Debre Markos	10.4	37.76667
90	Abay	Middle N. 3	113031	Huluka	Nr. Ambo	8.95	37.88333
91	Abay	Middle N. 3	113032	Debes	Nr. Ginchi	9.06667	38.05
92	Abay	Middle N. 3	113033	Quashini	Nr. Addis Kidame	11.2	36.86667

(continued...)

7.2. Appendix 2: List of Hydrological Stations in Blue Nile (continued ...)

S_NO	MAIN_CATCH	SUB_CATCH	STATION_NO	RIVER_LAKE	SITE	LATITUDE	LONGITUDE
93	Abay	Middle N. 3	113034	buchiksi	Nr. Kidamaja	11.01667	36.7
94	Abay	Middle N. 3	113035	Ayo	Nr. Azena Town	10.66667	36.76667
95	Abay	Middle N. 3	113036	Lower Fettam	at Galebed	10.48333	37.01667
96	Abay	Middle N. 3	113038	Indris	at Guder	8.93333	37.75
97	Abay	Middle N. 3	113037	Debis	Nr. Guder	9.01667	37.76667
102	Abay	Rahad (8)	118001	Rahad	Nr. Metema	12.6	36.23333
103	Abay	Upper Nile (2)	112001	Abbay	Nr. Dessie	11.06667	38.18333
104	Abay	Upper Nile (2)	112002	Mugher	Nr. Chencho	9.3	38.73333
105	Abay	Upper Nile (2)	112003	Abbay	at Bahir Dar	11.6	37.4
106	Abay	Upper Nile (2)	112004	Andassa	Nr. Bahir Dar	11.5	37.48333
107	Abay	Upper Nile (2)	112005	Jemma	at Mouth	10.1	38.36667
108	Abay	Upper Nile (2)	112006	Jemma	Nr. Insaro	10.06667	38.66667
109	Abay	Upper Nile (2)	112007	Beressa	Nr. Debre Markos	9.66667	39.51667
110	Abay	Upper Nile (2)	112008	Shy	Nr. Tsehay Senna	10.25	39.56667
111	Abay	Upper Nile (2)	112009	Wizer	Nr. Mehal Meda	10.23333	39.68333
112	Abay	Upper Nile (2)	112010	Chacha	at Chacha	9.53333	39.46667
113	Abay	Upper Nile (2)	112011	Shy	Nr. Mehal Meda	10.25	39.56667
114	Abay	Upper Nile (2)	112012	Aleltu	Nr. Chancho	9.35	38.68333
115	Abay	Upper Nile (2)	112013	Deneba	Nr. Chancho	9.26667	38.71667
116	Abay	Upper Nile (2)	112014	Sibilu	Nr. Chancho	9.23333	38.75
117	Abay	Upper Nile (2)	112015	Roba	U.S. Rod. Cha.	9.25	38.76667
118	Abay	Upper Nile (2)	112016	Shina	Nr. Adiet	11.25	37.5
119	Abay	Upper Nile (2)	112017	Muga	Nr. Dejen	10.16667	38.15
120	Abay	Upper Nile (2)	112018	Azuari	Nr. Mota	10.96667	38.01667
121	Abay	Upper Nile (2)	112019	Tigdar	Nr. Gunde Woin	10.88333	38.01667
122	Abay	Upper Nile (2)	112020	Gebregura	Nr. Degolo	10.41667	39.25
123	Abay	Upper Nile (2)	112021	Selgi	Nr. Kabe	10.75	39.41667
124	Abay	Upper Nile (2)	112022	Mechela	Nr. Kabe	10.73333	39.35
125	Abay	Upper Nile (2)	112023	Jogola	at Wereilu	10.58333	39.43333
126	Abay	Upper Nile (2)	112024	Tumelie	at Wereilu	10.6	39.41667
127	Abay	Upper Nile (2)	112025	Gerbagura	at Gebra Guracha	9.8	38.4
128	Abay	Upper Nile (2)	112026	Beshillo	Nr. Wegel Tena	11.48333	39.25

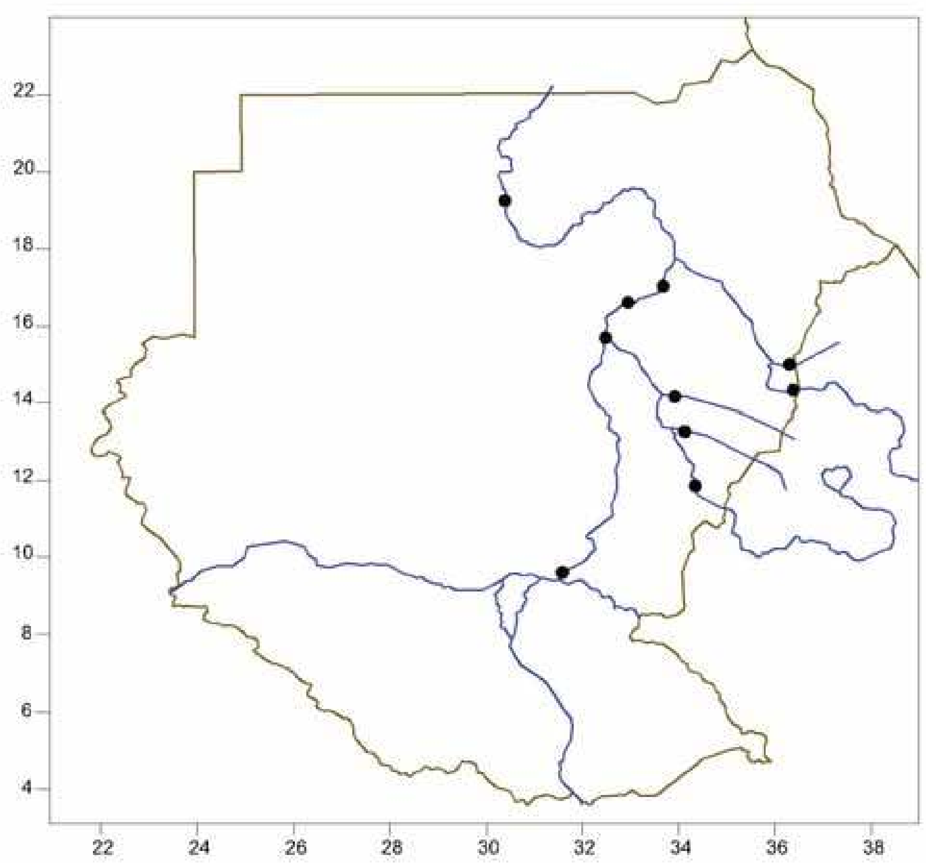
(continued...)

7.2. Appendix 2: List of Hydrological Stations in Blue Nile (continued ...)

S_NO	MAIN_CATCH	SUB_CATCH	STATION_NO	RIVER_LAKE	SITE	LATITUDE	LONGITUDE
129	Abay	Upper Nile (2)	112027	Aleltu	Nr. Muka Ture	9.65	38.95
130	Abay	Upper Nile (2)	112028	Rogi Jida	Nr. Muka Ture	9.63333	39
131	Abay	Upper Nile (2)	112029	Robigumero	Nr. Lemi	9.75	39
132	Abay	Upper Nile (2)	112030	Teme	Nr. Mota	10.41667	37.98333
133	Abay	Upper Nile (2)	112031	Suha	Nr.l Bichena	10.41667	38.18333
134	Abay	Upper Nile (2)	112032	Boreda	Nr. Mekane Selam	10.75	38.78333
135	Abay	Upper Nile (2)	112033	Lege Cora	Nr. Mekane Selam	10.76667	38.78333
136	Abay	Upper Nile (2)	112034	Jemma	Nr. Lemi	9.91667	38.9
137	Abay	Upper Nile (2)	112035	Weleka	Nr. Borena	10.76667	38.91667
138	Abay	Upper Nile (2)	112036	Mendel	Nr. Tis Abbay	11.48333	37.56667
139	Abay	Upper Nile (2)	112037	Sedie	Nr. Mota	11.03333	37.9
140	Abay	Upper Nile (2)	112038	Yeda	Nr. Amber	10.25	37.81667
141	Abay	Upper Nile (2)	112039	Chena	Nr. Istay	11.61667	38.03333
142	Abay	Upper Nile (2)	112040	Wenka	Nr. Istay	11.61667	38.06667

a) Sudan

Station Name	HFNationalID	Lon	Lat	Start Date	End Date	No. of Years	Gauge zero	Min	Max	SD
Dongola	1100092	30.53	19.17	1890	2007	118	212.03	25	1096	161.8
Hassanab	1100042	34.65	17.65	1923	2007	85	332.29	10	910	196.2
Tamaniat	1100012	32.65	15.97	1912	2007	96	358.73	41	848	14.7
Khartoum	900152	32.52	15.60	1904	2007	104	363	0	955	152.8
Hawata	902032	34.62	13.40	1971	2007	37	420.5	0	18	5.1
Giwasi	901032	34.10	13.32	1971	2007	37	416.48	0	92	168.5
Eddiem	900012	34.98	11.23	1962	2007	46	481.2	3	934	30.7
Malakal	800092	31.67	9.55	1906	2007	102	375.19	44	193	24.6
Kubur	1000012	36.00	14.08	1966	2007	42	470.535	0	359	156.6
Wad Elheliew	1001012	36.25	14.25	1966	2007	42	478.484	0	996	59.3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7.3. Appendix 3: Models for Blue Nile and Nile

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
MODELS FOR THE ABAY/BLUE NILE BASIN					
Tesfahun, D.; Moges, S.; Awulachew, S. B.	2006	Two parameter based conceptual rainfall-runoff models from the Upper Blue Nile	Uses the water accounting principle based on the MoWBAL model originally developed by Awulachew and used in the Rift Valley Lakes, Ethiopia	Monthly climatological and hydrological data combined with GIS based basin information	Possible from authors
Mishra, A.; Hata, T.	2006	A grid-based runoff generation and flow routing model for the Upper Blue Nile Basin	Thornthwaite-Mather water balance model on 0.5 degree grid, in combination with the runoff routing model for large river systems	"Hydro-climate-GIS database" developed by the authors; observed flow data from El Deim station in Sudan from 1980-1985, obtained from the Ministry of Irrigation and Water Resources, Sudan; mean monthly temperature and precipitation for grid cell from University of Delaware (Global Air Temperature and Precipitation Data Archive), website stated in text	Japan Society for the Promotion of Science; Kobe University
Antar, M. A.; Elassiouti, I.; Allam, M. N.	2006	Rainfall-runoff modelling using artificial neural networks technique: a Blue Nile Catchment case study	Rainfall-runoff based on the ANN model (artificial neural network)	GIS-derived MAP (mean areal precipitation) initially estimated by the trispectral rainfall estimation approach; Deim runoff measurements-outlet of Blue Nile at Ethiopian/Sudanese border)	Possibly from Nile Forecast Center, Egypt Ministry of Water
The Centre for Environmental Economics and Policy in Africa (CEEPA)	2006	Vulnerability of water resources of Lake Tana, Ethiopia, to climate change	WATBAL	Monthly cumulative rainfall, temperatures, relative humidity, streamflow of the Abay at Lake Tana, Bahir Dar, Ethiopia outlet (1878-1997)	Possibly from CEEPA (http://www.ceepa.co.za/climange_change/project.html)

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Mishra, A.; Hata, T.; Abdelhadi, A.W.; Tada, A.; Tanakamaru, H.	2004	Recession flow analysis of the Blue Nile River	Three different storage–outflow algorithms; single linear, non-linear and multiple linear reservoir	Mean '10-days' flow of the Blue Nile for the years 1912–1913 and 1996–1997	Japan Society for the Promotion of Science; Kobe University
Conway, D.	1997	A water balance model of the Upper Blue Nile in Ethiopia	Thornthwaite Mather water balance combined with the large-scale hydrological modeling approach	Roseires and El Deim runoff in Sudan; Lake Tana outlet flow and lake level; Rainfall and temperature from FAO publication; Rainfall from gauges; and PE predicted by Penman (four combinations of available data: Thornthwaite; elevation; latitude, longitude, elevation; and latitude, longitude, Thornthwaite)	Potential of model discussed: distributed parameter values, improvement of RF estimate. PhD thesis funded by Stockholm Environmental Institute
Johnson, P. A.; Curtis, P. D.	1994	Water-balance of Blue Nile River Basin in Ethiopia	General water balance based on Van der Beken and By loos (1977); Schaake and Chunzhen (1989)	Data tables presented from summary of USBR (1964), Gamachu (1977), and Shahin (1985); Rainfall gauges in Chemoga and Mugher watersheds; remaining watershed Rainfall from gauges near to watersheds (weighted by distance and comparison of annual Rainfall)	University of Avignon, France; Addis Ababa University
Conway, D.; Hulme, M.	1996	The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt	Similar to that of Vorosmarty et al. of Amazon and Zambezi rivers, 10 minute grids, PET calculated by Thornthwaite or Penman, Soil Water Holding Capacity invariant	Lake Victoria outflows, 1956-1978; runoff at El Deim (1951-1997) (World Bank 1989; Hurst and Philips 1933)	Climatic Research Unit, University of East Anglia, UK

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
El-Fandy, M. G.; Ashour, Z. H.; Taiel, S. M. M.	1994	Time series models adoptable for forecasting Nile floods and Ethiopian rainfalls	Box and Jenkins (1976) technique: auto-regressive integrated moving average model deemed most appropriate because of the time series of a periodic nature (Ethiopian rainfall and floods). Drought history and trends and periodicities analyzed. Forecast modeling	Levels of seasonal Nile floods (maximum, minimum) 625-1457 (835 years); Total annual rainfall for Addis Ababa (1907-1984); Yearly total discharge Ethiopian Plateau: Sobat at Hillet Doleib, Blue Nile at Roseris, Dinder, Rahad, and Atbara, Equatorial lake plateau supply at Aswan Dam (1912-1982); Total annual discharge at Aswan (1871-1982). Location of data within literature mentioned in text.	Cairo University, Giza, Egypt
Tsintikidis, D.; Georgakakos, K.P.; Artan, G. A.; Tsonis, A. A.	1999	A feasibility study on mean areal rainfall estimation and hydrologic response in the Blue Nile region using METEOSAT images	Bi-spectral frequency analysis to develop daily Mean Areal Precipitation (MAP) with 3-hourly METEOSAT visible and infrared images; hydrological modeling = soil water accounting model and sub-surface runoff production and groundwater loss and kinematic routing	Visible and Infrared imagery for Blue Nile Basin; gauge network within basin	Hydrologic Research Center, CA; NileForecast System (NFS)
Kebede, S.; Travi, Y.; Alemayehu, T.; Marc, V.	2006	Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile Basin, Ethiopia	Annual water budget of Lake Tana at a monthly time step: simulation of lake level variation	Components of water balance: Bathymetry, precipitation (1960-1992, Bahir Dar), river inflow (measured 1921-1926, 1928-1933, and 1959-1992 and estimated with Runoff coefficient), lake levels, and outflow (lake levels and outflow 1921 intermittently and from 1950 to present—datum shift)	
Eldaw, A. K.; Salas, J. D.; Garcia, L. A.	2003	Long-Range forecasting of the Nile River flows using climatic forcing	Sea surface temperatures and precipitation correlated linearly with Nile River flows	Streamflow data from the Ministry of Public Works and Water Resources of Egypt. Data from Blue Nile at El Deim extended using correlation analysis for years 1964-1994	University of Colorado

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Moussa, O. M.	1991	Hydrological regression sediment-yield model for ungaged stations along the Blue Nile coarse	Assumes no variation in suspended sediment (SS) concentration in river and no deposition of SS particles in both the Sennar and Roseires rivers	Egyptian Nile Control Department, Discharges of Nile 1939-1952 60 observations of water discharge at Sennar, Dinder, Rahad and Khartoum	Military Technical College, Cairo
Moussa, O. M.; Bedford, K. W.; Smith, S. E.	1989	Satellite data based sediment-yield models for the Blue Nile	Linear regression taken between the Global Vegetation Index and suspended sediment discharge	Ten day mean values of the water discharge for August, September and October of 1981-1984 (obtained from the Egyptian Nile Control Department)	From the author
MODELS FOR THE NILE BASIN					
Mohamed, Y. A.; Bastiaanssen,W.G.M; Savenije, H. H. G.	2004	Spatial variability of evaporation and moisture storage in the swamps of the upper Nile studied by remote sensing techniques	SEBAL algorithm to derive energy balance components at the land surface from NOAA-AVHRR images	Sobat sub-basin data based on Sutcliffe and Parks (1999). SEBAL-based daily evaporation estimates tested with data from ECHIVAL Field Experiment in a Desertification-threatened Area (EFEDA)-Spain, Hydrologic Atmospheric Pilot Experiment (HAPEX)-Niger and Heihe river basin Field Experiment (HEIFE)-China, to have an error of single day events of 17% or lower on a 1 km^2 scale	Delft University, the Netherlands

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
NBCBN-RE	2005	Nile Basin Capacity Building Network (NBCBN): GIS-based watershed modeling in the Nile Basin countries	Sediment model of Simiyu River Basin (Tanzania). SWAT was used for flood hazard mapping and mitigation, model assessment for sediment yield estimation, water quality inventory for Lake Victoria watersheds, definition of an integrated watershed management geo-database, and conceptual design of watershed management system	Riverflow data collected for 3 gauging stations; Seven-day sediment dataset from University of Dar es Salaam; spatial data from Lake Victoria Environmental Management Project and United States Geological Survey (USGS); geographical and morphological characteristics from Global Positioning System (GPS)	
RELATED MODELS BUT NOT APPLIED IN NILE BASIN					
Vallet-Coulomb, C.; Legesse, D.; Gasse, F.; Travi, Y.; Chernet, T.	2001	Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia)	Three climatic approaches to determine ET: lake energy, Penman, and Complementary Relationship Lake Evaporation (CRLE); Water balance for comparison	Thirty years of hydrometeorological data (Ziway Station): monthly average temperature, air humidity, sunshine duration, rainfall, lake level, and river discharge	CEREGE-CNRS/UMR and Addis Ababa University
Billi, P.; Caparrini, F.	2006	Estimating land cover effects on evapotranspiration with remote sensing: a case study in Ethiopian rift valley	Multi-scale variational assimilation algorithm, 30 minute time step, 1 km grid; comparison of remotely sensed land surface temperature to measured radiation temperature, etc.	AVHRR on NOAA satellites; measurements of barometric pressure, radiation, temperature, soil surface temperature, soil moisture, and wind profiles for short period	Italian Space Agency, National Research Council, Agenzia 2000

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Legesse, D.; Vallet-Coulomb, C.; Gasse, F.	2003	Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia	Distributed precipitation run off model with HRU (Hydrological Response Unit)	Data for 1985-1995 from existing data and calibrated against discharge data (rainfall from Ethiopian Meteorological Service and discharge from Ministry of Water Resources); HRU from Arc View and ILWIS, GIS programs for delineating basins and land cover differentiation; daily solar radiation (Addis Ababa University)	CEREGE-CNRS/UMR and Addis Ababa University
Bryson, R. A.; Bryson, R. U.	2000	Site-specific high-resolution models of the monsoon for Africa and Asia	Global glacial model (ice albedo effect) developed first, then hemispheric temperature model (solar irradiance). This was then scaled to regional level and adjusted using temperature gradient and latitudes of anticyclones and jet streams	Historical temperature gradient (hemispheric temperature model using solar irradiance) led to calculation of latitude, edge of vortex indicates subtropical anticyclones; monthly rainfall of Blue and White Nile headwaters generated from temp model; overflow of lake level at Lake Moeris (Hassan 1985)	Institute for Environmental Studies (University of Wisconsin)
Coe, M. T.	2000	Modeling terrestrial hydrological Systems at the continental scale: testing the accuracy of an atmospheric GCM	Global hydrological routing algorithm (HYDRA) simulates seasonal river discharge and changes in surface water level on spatial resolution 5' longitude x 5' latitude for Americas, Europe, Asia, and Africa and large river systems (St. Lawrence and Nile)	daily or monthly mean averages of runoff, precipitation, and evaporation either from GCM output or observations; hydrologic network is derived from two 59 x 59resolution (ø10 km^3 10 km at the equator) global DEMs: 1) TerrainBase from the National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (which is based on the original NOAA product ETOPO5); and 2) GLOBAL DEM5 (1995) from Geophysical Exploration Technology Ltd. (GETECH 1995) (which is based on ETOPO5 and independent observations)	Climate, People, and Environment Program, Institute for Environmental Studies, University of Wisconsin, Madison

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Elshamy, M. E.; Wheater, H. S.; Gedney, N.; Huntingford, C.	2006	Evaluation of the rainfall component of a weather generator for climate impact studies	Rainfall disaggregation model currently used to convert monthly rainfall totals down to the daily time step for weather generator model (four variables generated = precipitation, temperature, radiation, and relative humidity)	Daily data from a network of rain gauges covering the Nile Basin and contrasted with data from a relatively dense rain gauge network from the Blackwater Catchment, in the Southeast of the UK; Daily rainfall data from Nile Basin Hydrometeorological Information System (NBHIS); gauges from Kericho and Kitale (Equatorial Lakes Basin) and Addis Ababa (Blue Nile Basin) for full data collection	Civil and Environmental Engineering, Imperial College London, Met Office Joint Centre for Hydro-Meteorological Research.
Guo, S. L.; Kachroo, R. K.; Mngodo, R. J.	1996	Nonparametric kernel estimation of low flow quantiles	Nonparametric kernel estimation model to estimate low flow quantiles	Annual minimum low flow data from El Deim station (1921-1991) and Monte Carlo simulation tests	Water Resources, Univer sity of Dar es Salaam, Tanzania
Kondrashov, D.; Ghil, M.	2006	Spatio-temporal filling of missing points in geophysical data sets	Singular Spectrum Analysis (SSA) for filling gaps in datasets (univariate record) and multi-channel SSA (M-SSA) for multivariate record: iterative gap filling	Datasets from oceanography, hydrology, atmospheric sciences, and space physics: global sea-surface temperature, flood-water records of the Nile River, the Southern Oscillation Index (SOI), and satellite observations of relativistic electrons	Department of Atmo spheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, LA, and Department of Geo sciences and Laboratoire de M´et´eorologie Dynamique (CNRS and IPSL), Ecole Normale Sup´erieure

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Liden, R.; Harlin, J.	2000	Analysis of conceptual rainfall-runoff modelling performance indifferent climates	The HBV-96 model, conceptual rainfall-runoff model, was applied on four catchments located in Europe, Africa and South America (different climates)	Rainfall and evaporation data from various meteorological stations in or near the different catchments; Monte Carlo Simulation (MCS) for four catchments in Turkey, Tanzania, Zimbabwe and Bolivia	Department of Water Resources Engineering, Lund University, Sweden and Swedish Meteoro logical and Hydrological Institute (SMHI), c/o Department of Water Development, Zimbabwe
Miller, J. R.; Russel, G. L.; Caliri, G.	1994	Continental-scale river flow in climate models	River routing model to be used with grid box climate models for whole earth; routing model needs algorithm for river mass flow and river direction file which has been compiled for 4o x 5o and 2o x 2.5o resolution	Topography derived from National Geophysical Data Center (1988) 5 minute elevation data; monthly flow at mouth of world's major rivers (Nile included); river direction files based on world maps (Korzoun et al. 1977; Times of London 1967); Three basin-wide parameters introduced: river length weighted by source runoff, turnover rate and basin-wide speed	Department of Marine and Coastal Sciences, Cook College, Rutgers Univer sity; NASA/Goddard Space Flight Center, Institute for Space Studies, NYC; Hughes STX Corp., NYC

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Senay, G.B.; Verdin, J. P.	2004	Developing index maps of water-harvest potential in Africa	Runoff (watershed yield) from SCS curve number and rainfall from satellite derived; watersheds delineated from HYDRO_1K DEM; water-harvest index maps: based on availability of Runoff, evaporation losses, population density, and required watershed size needed to fill small storage reservoir	Africa"wide satellite"derived daily rainfall estimates (RFE) from 1998 through 2002 were used in this study. Blended satellite"gauge RFE images for the African continent are prepared at 0.1° (~10 km) spatial resolution (Xie and Arkin 1997)by an interpolation method that combines data from METEOSAT cold cloud duration (CCD), the Special Sensor Microwave/ Imager (SSM/I) of the Defense Meteorological Satellite Program, the Advanced Microwave Sounding Unit (AMSU) on board the NOAA "15 polar orbiter, and rain gauge data from Global Telecommunication System (GTS); Required datasets such as soil texture and annual evaporation were extracted from global datasets assembled by FAO (1994). Africa"wide population density maps were extracted from Landscan 2000 global dataset that is produced and distributed by Oak Ridge National Laboratory (Dobson et al. 2000); Daily runoff was calculated in ARC/INFO: GRID for each pixel with a spatial resolution of 10 km	US Geological Survey, Earth Resources Observa tion Systems (EROS) Data Center, Sioux Falls, South Dakota; Famine Early Warning System Project of the United States Agency for International Development (USAID) and a grant from the United States Department of Agriculture-Foreign Agricultural Service (USDA"FAS) Scientific Cooperation Research Program

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Tate, E.; Sutcliffe, J.; Conway, D.; Farquharson, F.	2004	Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100	Net basin supply water balance:direct rainfall series (Sene and Plinston 1994)	GCM data supplied by Climate Impacts LINK project; Agreed Curve, lake outflow (Institute of Hydrology 1984); rainfall series estimated for five main sub-catchments using regressions of annual total data	Center for Ecology and Hydrology and Heath, Barton, Oxfordshire; School of Development Studies, University of East Anglia, Norwich; UK Natural Environment Research Council (CEH, Wallingford)
Taylor, J. C.; van de Giesen, N.; Steenhuis, T. S.	2006	West Africa: Volta discharge data quality assessment and use	Hydrological distribution in Volta River to fill in missing data: statistically linear model and conceptual hydrological model, Thornthwaite-Mather	Potential evaporation (DGIRH) and rainfall (WRI, GGC compiled by CRU (New et al. 1999a,b), DGIRH), Penman's ET from CRU: vapor pressure, wind speed, and temperature; stream discharge (WRI and ORSTOM) for calibration and validation; digital elevation model (Land Processes 2004). If multiple datasets existed, statistical analyses were used to determine accuracy.	Simple spreadsheet, Biological and Environ mental Engineering at Cornell University
Ward, F. A.; Booker, J. F.; Michelsen, A. M.	2006	Integrated economic, hydrologic, and institutional analysis of policy responses to mitigate drought impacts in Rio Grande Basin.	Integrated basin-wide non-linear programming model was designed and constructed for the purpose of optimizing water demand and use levels for the Basin; tests whether institutional adjustments can limit damages caused by drought and identifies changes in water uses and allocations that result from those adjustments	Rio Grande Basin primary surface water source is high mountain snowpack, monsoon thunderstorms (Schmandt 2002), total annual streamflow (seven previous years in drought), basin inflow (Michelsen and Cortez 2003), population density; 80-90% of upper Basin used for irrigation	Rio Grande Basin Initiative Project, US Geological Survey, Agricultural Economics at New Mexico State University and Economics and Environmental Studies, Texas A&M

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Winsemius, H. C.; Savenije, H. H. G.; Gerrits, A. M. J.; Zapreeva, E. A.; Klees, R.	2006	Comparison of two model approaches in the Zambezi river basin with regard to model reliability and identifiability	Provide preliminary terrestrial storage estimates from two models in the Upper Zambezi, compared with estimates derived from the Gravity Recovery And Climate Experiment (GRACE) in a future study. First model: STREAM, GIS-based distributed and conceptual, Second: LEW (Lumped Elementary Watersheds)	Hydrology of Zambezi: uplands, wetlands and floodplains; Elevation maps; time series of 1960s used to calibrate water balance models (Global Historical Climate Network: http://daac.ornl.gov/S2K/safari.html; discharge time series (did not cover same period as rainfall data), more recent rainfall data generated from second version of the Climate Research Unit's (CRU) monthly grids (New et al. 2002). The grids (0.5 × 0.5 (km^2) are based on as much rainfall stations as could be found, e.g., from the Global Telecommunication Systems (GTS);	Delft University, the Netherlands
EROSION AND SEDIMENT YIELD MODELS APPLIED IN ETHIOPIA					
Bewket, W.; Sterk, G.	2005	Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia	Alternative to paired watershed and modeling: changes in streamflow patterns with reference to dynamics in land cover/use in a typical watershed, the Chemoga, in northwestern highland, Ethiopia	Aerial photographs and multispectral Spot image (Bewket 2002); Last 40 years of streamflow (staff gauge and rating curve) from Hydrology Department of the Ministry of Water Resources (MoWR) of Ethiopia; rainfall data-Debre Markos, National Meteorolgical Services Agency	Addis Ababa University, Ethiopia; Wageningen University, the Netherlands

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Haregeweyn, N.; Yohannes, F.	2003	Testing and evaluation of the agricultural non-point source pollution model (AGNPS) on Augucho catchment, western Hararghe, Ethiopia	AGNPS process-based model for estimating soil loss	Observed dataset of rainfall for an 11 year period (1983–1993); land use, runoff, sediment, and peak runoff rate were either not fully available or were not consistent. 1988-year data were used for model validation, 1990-year data for model calibration; primary data collection through field surveys of conservation practices, nutrient use, tillage practices, and identification of channel types, description and determination of their relative features such as width, depth, and side; secondary data used for Universal Soil Loss Equation (USLE) parameters adapted to study area, included meteorological records, river hydrometric measurements, sediment loss, land use and sociocultural data, obtained from Soil Conservation Research Project (SCRP) database	Dr Fekadu worked with AMAREW and is now in USA
Haregeweyn, N.; Poesen, J.; Nyssen, J.; Verstraeten, G.; de Vente, J.; Gerard, G.; Deckers, S.; Moeyersons, J.	2005	Specific sediment yield in Tigray-Northern Ethiopia: Assessment and semi-quantitative modelling	Calibrating and adapting the Pacific Southwest Inter-Agency Committee (PSIAC) and the Factorial Scoring Model (FSM) sediment yield assessment models to Ethiopian conditions	Field assessment (measurement, GPS) of trapped sediment and local farmer interviews about history of the reservoir; SAERT (Sustainable Agriculture and Environmental Rehabilitationin Tigray)	Mekelle University and KU, Leuven, Belgium; Zala Daget Collaboration Project "Success and failures of soil conservation and dam construction in Tigray highlands, Northern Ethiopia"

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7.3. Appendix 3: Models for Blue Nile and Nile (continued ...)

Authors	Date	Title	Brief description of model	Data sources	Model available? (Funding sources, author's institution)
Hengsdijk, H.; Meijerink, G. W.; Mosugu, M. E.	2006	Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia	(i) Bunds along field contours to improve water availability for crop production, (ii) mulching of crop residues to improve soil nitrogen stocks, and (iii) reforestation to reduce erosion evaluated by crop growth simulation model (WOFOST), a nutrient monitoring model (NUTMON) and a hydrological erosion model (LISEM), which are applied at field, farm and regional scale	WOFOST, field scale: prevailing solar radiation, temperature and amount and distribution of rainfall, soil properties (i.e., soil depth, water holding and infiltration capacity) and crop characteristics (i.e., length of growing cycle, photosynthetic characteristics and distribution of dry matter); NUTMON, farm scale: compilation of nutrient balances which provide insight into the magnitudes and causes of nutrient imbalances; LISEM, landscape scale: rainfall, rainfall interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and through fall, detachment by overland flow and sediment transport capacity	Dutch Ministry of Development Cooperation, and DLO-IC, the research program International Cooperation of Wageningen-UR, the Netherlands
Tamene, L.; Park, S. J.; Dikau, R.; Vlek, P. L. G.	2006	Analysis of factors determining sediment yield variability in the highlands of northern Ethiopia	Pearson's correlation, principal components and multiple regression were implemented to analyze the relationship between s ediment yield and catchment characteristics and to determine the major factors controlling the variability of sediment yield	Quantitative reservoir sediment deposition data were acquired for the 11 sites based on two approaches. For reservoirs that were dry during the fieldwork, pit-based surveys were conducted, and for those that were full of water, bathymetric surveys were performed (Tamene 2005); Land use and cover maps 15 m resolution ASTER images (near IR), GPS, aerial photographs, DEMs, surface lithology could serve as a proxy for soil data to estimate erodibility potential (e.g., Evans 1997; Fargas et al. 1997; Bull et al. 2003)	University of Bonn, Seoul National University

(continued...)

7.4. Appendix 4: List of sediment stations and data availability (Ethiopia and Sudan)

a) Ethiopia (the data stations are lists. In majority of the cases, data is sporadic and limited in actual measurements)

S.No	*File Name*	*Description*	*Source*
1	Addis Zemen (Ribb).xls	Sediment measurement records at Addis Zemen Station	MoWR Hydrology Department
2	Addis Zemen(bure).xls	Sediment measurement records at Addis Zemen Station	MoWR Hydrology Department
3	Amanual(Gaziginit).xls	Sediment measurement records at Amanual Station	MoWR Hydrology Department
4	Ambera (Yeda).xls	Sediment measurement records at Ambera Station	MoWR Hydrology Department
5	Ambessema(yelda).xls	Sediment measurement records at Ambessema Station	MoWR Hydrology Department
6	Assosa(Hoffa).xls	Sediment measurement records at Assosa Station	MoWR Hydrology Department
7	Bahir Dar(Abbay).xls	Sediment measurement records at Bahir Dar Station	MoWR Hydrology Department
8	Bambasi(mutusa).xls	Sediment measurement records at Bambasi Station	MoWR Hydrology Department
9	Bichena(Muga).xls	Sediment measurement records at Bichena Station	MoWR Hydrology Department
10	Bichena(Suha).xls	Sediment measurement records at Bichena Station	MoWR Hydrology Department
11	Debre Brehane(beressa).xls	Sediment measurement records at Debre Brehane Station	MoWR Hydrology Department
12	Debre Markos(Abahim).xls	Sediment measurement records at Debre Markos Station	MoWR Hydrology Department
13	Debre Zeite(u. chemoga).xls	Sediment measurement records at Debre Zeite Station	MoWR Hydrology Department
14	Dembecha(Gudla).xls	Sediment measurement records at Dembecha Station	MoWR Hydrology Department
15	Dembecha(Temecha).xls	Sediment measurement records at Dembecha Station	MoWR Hydrology Department
16	Estea Chena(chena).xls	Sediment measurement records at Estea Chena Station	MoWR Hydrology Department
17	Estey2(Wanka).xls	Sediment measurement records at Estey2 Station	MoWR Hydrology Department
18	Fincha(Neshi).xls	Sediment measurement records at Fincha Station	MoWR Hydrology Department
19	Fogeda(Arb gebeya).xls	Sediment measurement records at Fogeda Station	MoWR Hydrology Department
20	Galebr Mariam(L.Fettom).xls	Sediment measurement records at Galebr Mariam Station	MoWR Hydrology Department
21	Gori(Komise).xls	Sediment measurement records at Gori Station	MoWR Hydrology Department
22	Guder (Bello).xls	Sediment measurement records at Guder Station	MoWR Hydrology Department
23	Guder (Guder).xls	Sediment measurement records at Guder Station	MoWR Hydrology Department
24	Gundeweian(Tigdor).xls	Sediment measurement records at Gundeweian Station	MoWR Hydrology Department

(continued...)

7.4. Appendix 4: List of sediment stations and data availability (Ethiopia and Sudan) (continued ...)

S.No	*File Name*	*Description*	*Source*
25	Gutin (Tato).xls	Sediment measurement records at Gutin Station	MoWR Hydrology Department
26	Kabe(Mechela).xls	Sediment measurement records at Kabe Station	MoWR Hydrology Department
27	Kabie(Selgie).xls	Sediment measurement records at Kabie Station	MoWR Hydrology Department
28	Kosober(Ayo).xls	Sediment measurement records at Kosober Station	MoWR Hydrology Department
29	Lumame(Bagena).xls	Sediment measurement records at Lumame Station	MoWR Hydrology Department
30	Mankusa(Debohila).xls	Sediment measurement records at Mankusa Station	MoWR Hydrology Department
31	Mehal Meda(Shay).xls	Sediment measurement records at Mehal Meda Station	MoWR Hydrology Department
32	Mehal Meda().xls	Sediment measurement records at Mehal Meda Station	MoWR Hydrology Department
33	Mendel (Tis-Abbay).xls	Sediment measurement records at Mendel Station	MoWR Hydrology Department
34	Merawi (Bered).xls	Sediment measurement records at Merawi Station	MoWR Hydrology Department
35	Merawi (Gilgel abbay).xls	Sediment measurement records at Merawi Station	MoWR Hydrology Department
36	Metekel(Mandura).xls	Sediment measurement records at Metekel Station	MoWR Hydrology Department
37	Metekele(Ardie).xls	Sediment measurement records at Metekele Station	MoWR Hydrology Department
38	Motta(Azuari).xls	Sediment measurement records at Motta Station	MoWR Hydrology Department
39	Motta(Sede).xls	Sediment measurement records at Motta Station	MoWR Hydrology Department
40	Motta(Teme).xls	Sediment measurement records at Motta Station	MoWR Hydrology Department
41	Mukatura (Robi-Jida).xls	Sediment measurement records at Mukatura Station	MoWR Hydrology Department
42	Mukature (Aleltu).xls	Sediment measurement records at Mukature Station	MoWR Hydrology Department
43	Nedjo(Dila).xls	Sediment measurement records at Nedjo Station	MoWR Hydrology Department
44	Woreilu(Tamelle).xls	Sediment measurement records at Woreilu Station	MoWR Hydrology Department
45	Yechereka(Chereka).xls	Sediment measurement records at Yechereka Station	MoWR Hydrology Department

b) Sudan

The available sediment information gathered from the Blue Nile system

Nile reaches and canals	Name of stations	Data available
Main Nile	Main Nile at EL Karo	Aug–Sept 1999, Aug–Oct 2001
Blue Nile	Blue Nile at El Deim	June–Oct 1993
	Blue Nile at downstream Roseires	Jul–Sept 98 , Jun–Sept 1999, Jun–Oct 2001
	Blue Nile at Sennar	Jul–Oct 1993, Jul-Sept 96, 1998
	Blue Nile at Wad Alais	Jun–Oct 93, Jul–Oct 95, Jul–Aug 96, Jun–Aug 1999, Oct 2001
	Blue Nile at Wad Elmahi	Jul-Sept 1998, Jun–Sept 1999
Dinder River	Dinder at Gawis	Jul–Oct 93, Sept–Oct 96, Jun–Sept 2001
Rahad River	Rahad River at Hawata	June-Oct 1993, Jul–Oct 96, 2001
	Rahad main Canal	Jul–Sept 96
	Abu Rakham (Hawata, Supply canal)	Jul–Oct 96, Sept – Oct 2001
Gazira Canal	Gazira Main Canal at Sennar	June–Oct 95, 96, 97, 98, 1999, 2001
	New Gazira Canal at K57	Jul–Dec 95, Jul–Sept 96, Aug–Oct 1998 Jun-Oct 97, 1999, 2001
	Gazira Main Canal at K57	June–Oct 1999
	Old Gazira Canal at K57	Jun–Nov 95, Jul–Sept 96, June–Oct 97, 1998, 2001
Managil Canal	Managil Main canal Sennar	June–Oct 95, 96, 97, 98, 1999, 2001
	New Managil Canal at K57	Jun–Nov 95, Jul–Sept 96, June–Oct 97, 98, 1999, 2001
	Managil Main canal at K5	June–Oct 1999
	Old Managil Canal at K57	Jun–Nov 95, Jul–Sept 96, Jun–Oct 1997, 1998, 2001
	Shawal Major Canal at K57	Jun–Dec 95, Jul–Sept 96, June–Oct 97, 1998, Jun–Aug 1999, 2001
	Fahal Major Canal at K57	Jun–Nov 95, Jul–Sept 96, June–Oct 97, 98, 1999, 2001
	Zanada Major Canal	Jun–Nov 95, Jul–Sept 96, June–Oct 97, 98, 1999, 2001
Atebra River	Upstream and downstream Khashm Elgirba Dam during flushing	Every 3 hrs on 14/8/1999

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IWMI is a Future Harvest Center supported by the CGIAR

ISBN: 978-92-9090-699-5