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Water Balance Modelling for the Sudan's Four Basins of Blue Nile, White Nile, Atbara River, and Main Nile

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ABSTRACT

This study focuses on estimating the flow discharges along the Nile River and its tributaries in Sudan. Thus, a fifteen years' data record from the year 1983/1984 to the year 1997/1998 was employed to estimate the transmission losses using the water balance approach. The Nile River and its tributaries are divided into subsequent reaches. The transmission losses are calculated as a percentage of the inflow discharges to each reach. These losses were found to be 1% to 2% on the Blue Nile, 2% to 7% on the White Nile, 1% on Atbara River, 1% to 3% on the Main Nile. A spreadsheet model was then developed to calculate the average annual flow discharges at Dongola Station on the Main Nile. Another data record of nine years was used to validate the model. A good agreement was obtained between the measured and calculated discharges. The results of this research could be a part of a mutually acceptable modeling system in the Nile Basin region.

1. Introduction

For centuries, the flow discharges of the Nile River have been of vital importance to several African nations, including Egypt and Sudan. The main uses of the Nile River waters are directed towards agriculture and hydropower. Accurate forecasts of water availability are essential for efficient management of water resources facilities, like reservoirs and diversions [1]. The Nile River is the longest river in the world. Running through 6695 km, the Nile is major trans-boundary water in the globe. The Nile River Basin is a confluence of the Blue Nile stemming from Lake Tana in Ethiopia and the White Nile, stemming from Lake Victoria in Uganda. The Ethiopian waters constitute by far the greater share of the Nile. The Nile and its tributaries run through eleven countries, Burundi, Democratic Republic of Congo (DRC), Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The Basin is considered as the home to different people and culture, and over 350 million people live around. The fact that the Nile Water is the lifeblood for the people who live around it makes the cooperation and interactions among the riparian countries complex [2]. Although the Nile watershed is large, the portion contributing to stream flow is only about 1.6 million km^2, ending near the confluence of the Atbara River and the Nile [3]. The area of both Sudan and South Sudan represents 64% of the Nile Basin area and contributes to its flow annually with a considerable amount. The Nile Basin covers roughly 2.9 million km^2, which is almost one-tenth of the area of Africa [4]. Therefore, its water resources management and development will be directly affected by any activities in the Nile Basin. The Nile River has three main basins from which it obtains its flow; the Equatorial Lake Plateau in the South, the Sud (Bahr el Ghazal, Bahr El Gebal)

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region in the Center, and the Ethiopian Highlands in the East. Estimating the water losses is essential for a precise forecast of the water arriving High Aswan Dam (HAD) each year and in the hydrologic budget for the management of the Nile River water. This research focuses on estimating of the transmission losses from the Nile River and its tributaries in Sudan for the efficient management of the Nile Water. Quantitative assessment of channel transmission losses is required for estimating the flow components of a river basin or reach and the projections of design flows at the withdrawal and delivery points of the water diversion system [5]. Quantitative assessment of these losses from the Nile River and its tributaries is crucial in the prediction of the Nile flows arriving High Aswan Dam, but the approximation of the potential losses of water from the Nile River system is a difficult task [6]. The river system is vast and varied, encompassing many different features; climates, landscapes, and geographical features. The immense size of the Nile River system combined with the great variability of the system's flow has posed a persistent challenge to hydrologists to estimate the water losses [7]. The problem has attracted the attention of many well-known hydrologists, water resources engineers, and general scientists [8 and 9].

2. Purpose of the study

The main aim of this research is to estimate the flow discharges along the Nile River and its tributaries in Sudan by knowing the discharges at the sources on the Nile River and its tributaries. Also, as a second objective of this study is to explore the transmission losses from the Nile River and its tributaries in Sudan taking into account the new developments in the Nile basin. These developments include hydraulic structures, hydropower generation, and irrigation schemes.

3. Methodology

The hydrologic budget approach is considered as the most appropriate method for estimating the water losses. In this study, the water balance method is employed to determine the water losses along the Nile River and its tributaries in Sudan. The water losses are expressed as a lumped parameter in terms of percentage loss of total flow passing through the main stations on the Nile and its tributaries.

4. Description of the Nile River and its tributaries

The Nile River is formed by the confluence of the White Nile and the Blue Nile Rivers. Atbara River, a tributary of the Nile, is situated downstream of their junction, Figure (1) shows a map of the Nile River its tributaries [10].

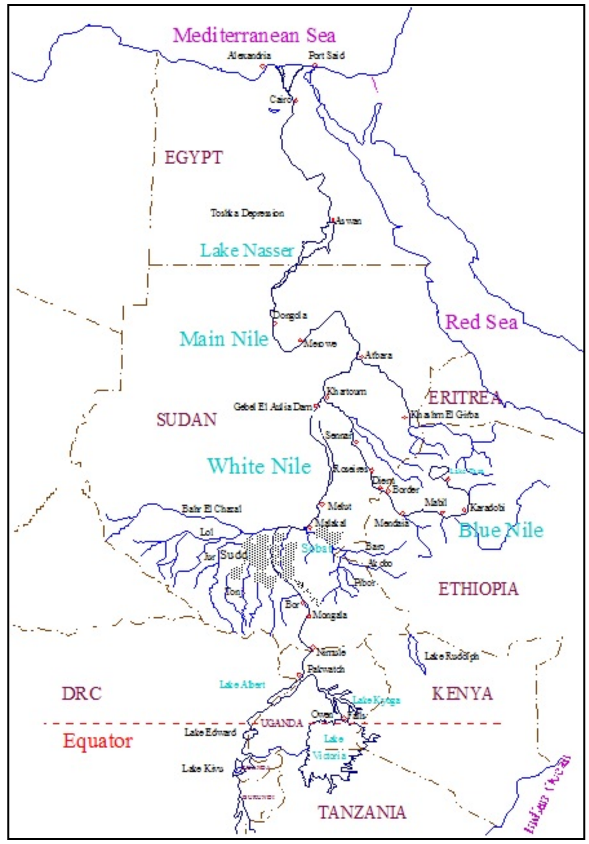

Fig. 1. Nile River Map

4.1. The Blue Nile

The bulk of the flow of the main Nile at Khartoum is provided by the Blue Nile, with its smaller tributaries the Dinder and Rahad. The Blue Nile drains a major part of the western Ethiopian highlands, with a small part of its basin subjected to storage in Lake Tana. The rainfall over this basin is limited to a single season, and the river flows are therefore concentrated in a short period [11]. Consequent problems of erosion and potential sedimentation make storage of flood waters difficult to achieve. Relatively small dams have been built at Sennar (1925) and at Roseires (1966) and its heightening (2012) near the Sudan-Ethiopian border, in order to provide water for irrigation in the Gezira and other areas. Also, hydroelectric power has been developed at these sites.

4.2. The White Nile

The regime of the White Nile from the Sobat mouth near Malakal to its confluence with the Blue Nile at Khartoum is relatively simple. Its balance over the years was influenced by the construction of the Jebel Aulia dam (1937) at the Blue Nile confluence to maintain downstream flows during the low flow seasons; this has resulted in wider areas of flooding and increased evaporation losses. Irrigation along the White Nile has been growing considerably over the years, with abstraction made easier by the raised levels of the river upstream of the dam.

4.3. The Atbara River

The Main Nile downstream of Khartoum flows north through the Sabaloka gorge and is joined 325 km north by its last tributary, the Atbara, which drains the northern portion of the highlands of Ethiopia and part of Eritrea. The Khashm El Girba reservoir as built on the upper Atbara in 1964 to store this runoff for irrigation, but the flashy nature of the inflow has resulted in considerable siltation. The river flows are reduced by evaporation and irrigation abstractions.

4.4. The Main Nile

Downstream of the Atbara mouth, the river flows in a series of wide loops through an arid area of successive cataracts and flatter reaches. The river flows are reduced by evaporation and irrigation abstractions. The Nile enters Egypt downstream of Wadi Halfa where the reservoir formed by the High Aswan Dam (HAD) now extends south of the border. A comparison of flows along the reach between Khartoum and Aswan reveals the effect of channel losses and abstractions as well as evaporation from the Aswan reservoir. The flow records downstream of Aswan reflect both the role of the reservoir in equalizing flows and successive diversions for irrigation down the final reach between High Aswan Dam and the Delta barrages.

5. Transmission losses and the new development

Water losses due to transmission by definition are the flow volume that is lost from a river or stream as water travels downstream. It includes seepage to groundwater, overbank flow that goes into floodplain depressions, wetlands and never returns to the river, evapo-transpiration from vegetation along the river fringe that access water directly from the river and evaporation from the water surface. New developments in the catchment will affect the transmission losses from this catchment. These developments include new dams, irrigation schemes and hydropower generation. Due to these developments, it is crucial to choose the hydrological record that is to be analyzed to quantify the transmission losses based on a period that considers all or at least most of these developments.

6. Hydrological data

To estimate the transmission losses along the Nile River and its tributaries in Sudan, observed river stages and flow discharges data were collected. These data are used to generate the rating curve (RC) at each station on the Nile River and its tributaries in Sudan. Using the most accurate rating curves available, the stages were transformed to discharges or stream flows. The available date was collected from different sources such as the Internet, some published papers, the Permanent Joint Technical Commission for Nile Waters (PJTC) annual reports, the Nile Basin Volumes, and the Nile Basin Initiative reports [12, 13, and 14].

The hydrological data includes the inflow to the river and its tributaries at the main stations (Diem, Malakal, Upper Atbara, Rahd and Dinder Rivers). Also, it includes the evaporation from the main reservoirs, and the water abstractions by the Sudanese side. The data of the water abstractions by Sudan are collected from the Sudanese Ministry of Water Resources and Electricity (WRE) through the PJTC. The available abstraction data to this study do not cover some parts on the Nile River and its tributaries in Sudan; as there are no available recorded data in these parts.

These parts such as the reach from Diem to Roseirs on the Blue Nile, the reach from the downstream of Gebal Aulia Reservoir to Khartoum (Mogren) on the White Nile, the reach from the downstream of Khashm El Girba Reservoir to Atbara Km 3 on the Atbara River, and the reach from Dongola to High Aswan Dam on the Main Nile. These data were assumed to be zero as there are no clear records for water abstractions in these parts. It is crucial that the authorities should adopt a data collection program in the future on a large scale for better management of the Nile water resources for the sake of the benefit of the people living around**.**

6.1 *Hydrological data collection and data processing*

The analysis of the hydrological data to quantify the transmission losses should satisfy the following:

- Availability of the hydrological data
- The hydrological data should be as accurate as possible.
- The period of the flow record should consider the new developments in the basin in Ethiopia and Sudan.

The new developments in the basin include; new irrigation schemes, new dams, reservoirs and pump stations. The most representative period that takes the above mentioned conditions into consideration is the period from the water year 1983/1984 to the water year 2009/2010. In data processing at a number of occasions, regression analysis is applied. For validation and in-filling of missing water level data a relation curve is established based on a polynomial relation between the observations at two water level gauging stations. Transformation of water levels into discharge series a discharge rating curve is created. The commonly used discharge rating curves are of a power type regression equation, where for each range of the independent variable (gauge reading) a set of parameters is established. The following main profiles were considered [15]:

6.1.1 Stations on the Blue Nile

- Diem, the hydrological measuring station on the Sudanese-Ethiopian border indicating the inflow of the Blue Nile from the Ethiopian Highlands to the Sudanese plains.
- Downstream of Roseirs Reservoir.
- Downstream of Sennar Reservoir.
- Khartoum on the Blue Nile, the final outlet of the Blue Nile immediately upstream of its junction with the White Nile.

6.1.2 Stations on the White Nile

- Malakal, the hydrological station on the White Nile indicating the contribution of White Nile, the Sobat River, and the Bahr el-Ghazal basin;
- Downstream of GebalAulia Reservoir.

6.1.3 Stations on the Atbara River

- Upper Atbara
- Downstream of khashm El-Girba Reservoir.
- Atbara Kilo 3, the outlet of the Atbara River immediately upstream of its junction with the Main Nile.

6.1.4 Stations on the Main Nile

- Tamniat station.
- Hasanab station.
- Downstream of Marawi Dam (the flow downstream of Marawi Dam).
- Dongola station.

Figure (2) shows the average annual flow discharges at Dongola Station on the Main Nile from the water year 1983/1984 to the water year 2009/2010. Also, Figure (3) shows the inter-annual variability of the Nile Flows at High Aswan Dam, HAD [16].

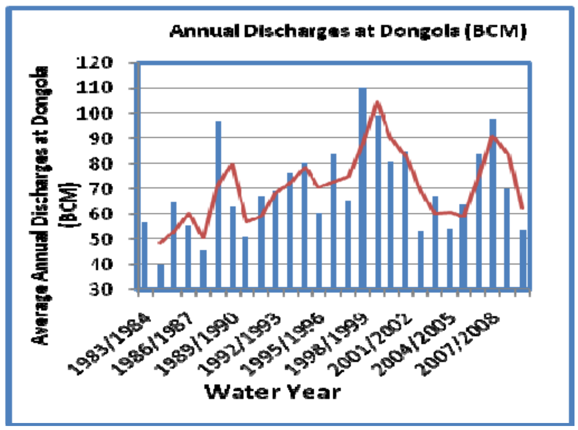

Fig. 2. Average Annual Discharges at Dongola Station

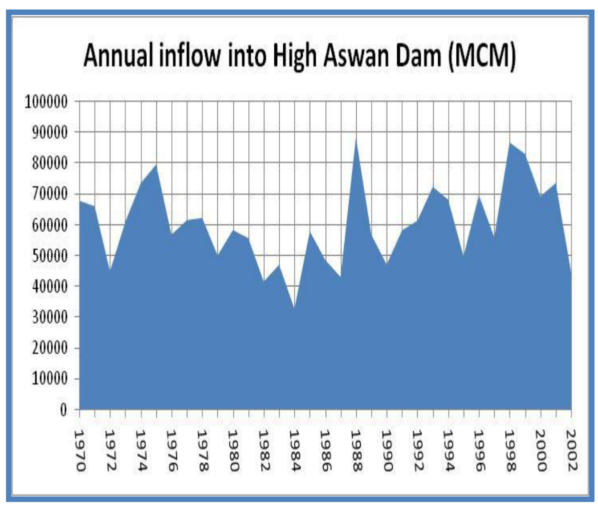

Fig.3. Inter-annual variability of Nile flows at High Aswan Dam, HAD [16]

7. Water budget method

7.1. Water balance equation

In this study, the water balance for the Nile River and its tributaries in Sudan was evaluated by using the annual values for terms in the basic equation:

$$Q_I = Q_O \pm \Delta S + L \qquad (1)$$

where

Q_I: the inflow discharge, (m^3/s)
Q_O: the Outflow discharge, (m^3/s)
ΔS: the net changes in the reach, (m^3/s)
L: the water losses in the reach, (m^3/s)

7.2. River reaches

The Nile River and its tributaries in Sudan are divided into reaches. This is to determine the transmission losses in each reach as a percentage of the total inflow to the reach. Average annual discharges are used in the calculation of the water losses for each reach. The reaches of the Blue Nile, the White Nile, the Main Nile and Atbara River are discussed here individually. As the average annual discharges are used, then Equation 1 can be written in the form:

$$Q_I = Q_O + L \qquad (2)$$

where

Q_I: the inflow to the reach, (m^3/s)
Q_O: the outflow from the reach, (m^3/s)
L: the water losses through transmission and evaporation, (m^3/s)

Part of the available data is used to deduce the transmission losses in the Nile and its tributaries in Sudan. This part is from the water year 1983/1984 to the water year 1997/1998. Some data of the other part are to be used for validation of the outcome.

7.2.1 The Blue Nile

The Blue Nile is divided into 3 reaches and the water balance equation is applied in order to determine the water losses for each reach as a percentage of the total inflow to the reach. The Blue Nile reaches are as follow:

- Diem – Roseirs
- Roseirs – Sennar
- Sennar – Khartoum

7.2.2 The White Nile

The White Nile is divided into 2 reaches and the water balance equation is applied to each reach in order to determine the water losses for each reach as a percentage of the total inflow to the reach. The White Nile reaches are as follow:

- Malakal – Gebel Aulia
- Gebel Aulia – Khartoum

7.2.3 The Atbara River

The Atbara River is divided into 2 reaches and the water balance equation is applied to each reach in order to determine the water losses for each reach as a percentage of the total annual inflow to the reach. The Atbara River reaches are as follow:

- Upper Atbra – KhashmGirba
- KhashmGirba – Atbara Km 3

7.2.4 The Main Nile

The Main Nile is divided into 5 reaches and the water balance equation is applied to each reach in order to determine the water losses from each reach as a percentage of the total annual inflow to the reach. The Main Nile reaches are as follow:

- Khartoum – Tamaniat
- Tamaniat – Atbara
- Atbara –Marawi
- Marawi – Dongola
- Dongola–High Aswan Dam

Table (1) shows flow discharge estimation at the mouth of each reach and, also it shows the transmission losses as computed by the water balance method.

Table 1. Determination of the transmission losses percentage

Reach No.	River	Reach Name	Average Annual Inflow (BCM)	Average Annual Outflow (BCM)
1	Blue Nile	Diem -Roseirs	48.60	47.70
2		Roseirs - Sennar	47.70	38.80
3		Sennar[a] – Khartoum[b]	42.40	41.60
1	White Nile	Malakal – GebalAulia Reservoir	30.80	24.80
2		GebalAulia Reservoir – Khartoum (Mogren)[c]	24.80	24.30
1	Atbara River	Upper Atbara[d]– Khashm El-Girba Reservoir	13.7	11.90
2		Khashm El-Girba Reservoir – Atbara Km 3	11.90	11.80
1	Main Nile	Khartoum[e] - Tamaniat	65.90	65.10
2		Tamaniat - Hasanab	65.10	62.80
3		Hasanab[f] – Marawi Dam	74.60	71.70
4		Marawi Dam – Dongola	71.70	70.70
5		Dongola – High Dam[g]	70.70	60.00

Table 1. Continue

Average Annual Abstractions by Sudan (BCM)	Average Annual Evaporation from Reservoirs (BCM)	Average Annual Transmission Losses (BCM)	%Losses
0.00	0.40	0.50	1.03
7.60	0.30	1.00	2.10
0.40	0.00	0.40	0.94
1.30	2.50	2.20	7.14
0.00	0.00	0.50	2.02
1.50	0.20	0.10	0.73
0.00	0.00	0.10	0.84
0.20	0.00	0.70	1.06
0.40	0.00	2.00	3.07
0.10	2.00	0.70	0.93
0.20	0.00	0.70	0.98
0.00	10.00	0.70	0.99

The superscript letters (a – g) in the third column of Table 1 are explained as follows:

a) The Summation of the average annual discharge of Sennar Reservoir and average annual discharge of the Dinder and Rahd tributaries.
b) The Khartoum Station on the Blue Nile immediately upstream of its junction with the White Nile.
c) The Khartoum Station at "Mogren" on the junction of the Blue Nile and White Nile
d) The summation of the average annual flow discharges of Atbara and Setit Rivers.
e) The summation of the average annual flow discharges of White Nile and Blue Nile.
f) The summation of the average annual flow discharges at Hasanab Station and Atbara River Km 3 Station.
g) The average annual flow discharge reaches High Aswan Dam (HAD).

8. Estimation of the flow discharge at Dongola

The flow discharges along the Nile River and its tributaries in Sudan can be estimated by knowing the flow discharges at the sources on the Nile River and its tributaries (Deim, Malakal and Upper Atbara) and the transmission losses percentages as calculated in this study. Dongola station is considered as one of the most important flow discharges measuring station on the Nile River as these discharges are used to quantify the water quantities arriving Lake Nasser and consequently quantify the water arriving Aswan. Also, the discharges at Dongola are used to estimate the water losses of Lake Nasser using the water balance approach. The flow discharges at Dongola are computed using the rating curve that relates the water level to the flow discharge.

8.1. Water balance model development

A spread sheet model was developed to calculate the average annual flow along the Nile River and its tributaries in Sudan. In the spread sheet model Figure 4, the following items are represented:

- The different reaches of the Nile and its tributaries.
- The different dams and reservoirs along the Blue Nile, the White Nile, the Atbara River, and the Main Nile.
- The Evaporation from the different reservoirs.
- The abstraction from the Nile and its tributaries by Sudan.
- The flow discharges at the main stations, i.e. Diem on the Blue Nile, Malakal on the White Nile, and Upper Atbara on the Atbara River.
- The percentage water losses from the different reaches along the Nile and its tributaries.
- The discharges of Rahd and Dinder reach at the four months of the flood season so, their discharges are added to the model directly.

By knowing the water losses (transmission, evaporation) and the flow passing the main stations, the average annual flow discharges at any station on the Nile River and its tributaries can be estimated. The spread sheet model was validated by comparing the discharges as calculated by the model and that was calculated by the rating curve for water years other than that was used in the working out of the transmission losses. The model was used to calculate the discharges at Dongola Station for the water years 1998/1999 to 2006/2007. In Figure (4), which is a screen shot of the spread sheet model, the average annual flow that passed Dongola station in the water year 2003/2004 was calculated by knowing the annual average flow at the main stations and the percentage of the water losses along the Nile River and its tributaries.

Table (2) shows a comparison between the annual flow discharge at Dongola as determined by the rating curve and that is calculated by the spreadsheet model for different water years. It shows also the differences between these discharges and the percentages of these differences. It can be seen from

Table 2 that the differences range from 0.2% to 4.2%. These differences could be due to the data accuracy and the missing data for water abstractions by Sudan in some parts on the Nile River and its tributaries. Also, Figure (5) shows that the model predicts well the flow discharges data at Dongola Station as these data are all well distributed around a 45 degrees line.

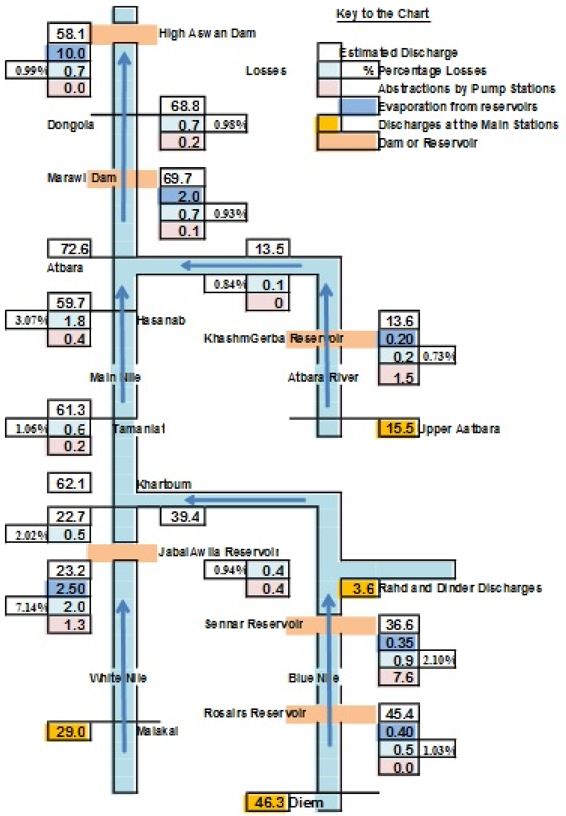

Fig. 4. Demonstration of the spread sheet model.

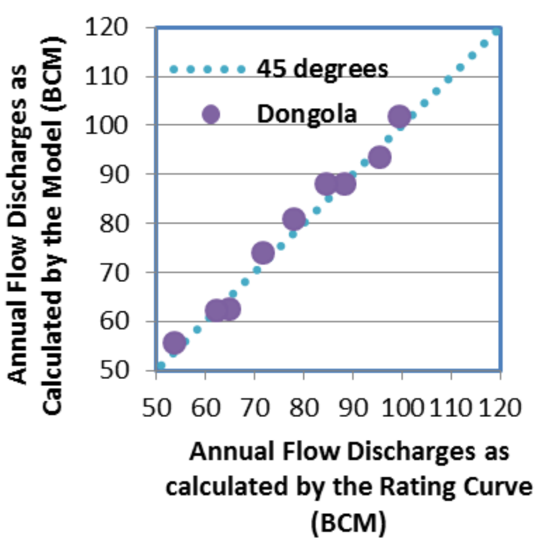

Fig. 5. Measured vs. calculated discharges at Dongola

Table 2. Measured vs. calculated discharge at Dongola Station using the spreadsheet mode.

Water Year	Annual Discharge (BCM)		Difference	% Difference.
	Rating Curve	Model		
1998/1999	99.6	101.8	2.2	2.2
1999/2000	95.5	93.6	-1.9	2.0
2000/2001	78.1	81.0	2.9	3.7
2001/2002	88.4	88.2	-0.2	0.2
2002/2003	53.6	55.7	2.1	3.9
2003/2004	71.8	68.8	-3.0	4.2
2004/2005	64.9	62.5	-2.4	3.7
2005/2006	62.2	62.1	-0.1	0.2
2006/2007	84.7	88.1	3.4	4.0

9. Conclusions and recommendations

9.1 Conclusions

From the results of this research and analysis discussed before, it can be concluded that:

- Quantitative assessment of the transmission losses in rivers is required in the estimation of flow components of a river basin.
- A water budget method was used in this research to quantify the transmission losses along the Nile River and its tributaries in Sudan.
- The Nile River and its tributaries are divided into consequent reaches and the water balance approach was applied in order to calculate the transmission losses at each reach.
- The water losses are expressed as a percentage of the average annual flow discharges of the inflow into each reach.
- The research output show that:
    - The water losses at 67% of the reaches are in the range of 1% of the average annual flow discharge that passes through a specified reach.
    - The water losses of 17% of the reaches are in the range of 2%
    - The water losses of the rest of the reaches are in the range of 3% - 7%
- The high losses of water occur in the reach of Malakl-Gebel Aulia on the White Nile. This reach is characterized by almost flat slope and occupies vast area.
- A spreadsheet model was developed to calculate the average annual discharges at Dongola station on the Main Nile by knowing the transmission losses and the flow passes the main stations on the Nile

River and its tributaries for different water years.
- A comparison between the average annual flow discharges at Dongola as calculated by the rating curve and that was calculated by the spreadsheet model shows some differences in the range of 0.2% to 4.2%.
- These differences could be due to the data accuracy and the missing data for water abstractions by Sudan in some parts on the Nile River and its tributaries.
- The results of this research can be used in estimating the river flow at any station along the Nile River and its tributaries in Sudan by predicting the flow discharges at the sources (Diem, Malakal, Upper Atbara and Rahd and Dinder rivers).

9.2 Recommendations

From the study results and conclusions, it can be recommended that:
- The results of this research could be used as a basis of a new methodology for estimating of the flow arriving High Aswan Dam. This can be done by forecasting the flow at the sources and by knowing the transmission losses percentage, the flow at High Aswan Dam can be calculated.
- The results of this research could be one of the elements of a modeling system in the Nile Basin region.
- It is recommended to establish a data collection program to collect the water abstractions by Sudan as accurate as possible for better results.

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Abbreviations

BCM: Billion Cubic Meters
DRC: Democratic Republic of Congo
HAD: High Aswan Dam
MCM: Million Cubic Meters
M: Model
NWS: Nile Water Sector
RC: Rating Curve
PJTC: The Permanent Joint Technical Commission for Nile Waters