Flood Propagation of the Blue Nile in the Sudan Using Muskingum Routing

Amira Abdel Rahim Abdel Gader Mekawi[1]

[1] Researcher, Hydraulics Research Station (HRS), Sudan.

Abstract
This work has dealt with the flood routing of the Blue Nile using the Muskingum method. It is well-recognized by hydrologists and water resources engineers that river flood routing models have a wide spectrum of sophistication. The Muskingum method which represents a linear reservoir concept is an example of the simplest form. The linear form of the Muskingum model has been widely applied to river flood routing because of its simplicity among the many models used for flood routing in natural channels and rivers. This study demonstrates the application of the Muskingum method for routing floods using daily flood data (from year 1965 to 2000) available for three reaches of the Blue Nile from Eddeim on the Ethiopian/Sudanese border to Khartoum the Sudanese capital. The study illustrates how to estimate the routing parameters using one day as a routing time interval without considering any of the limited channel cross sections data. The routing parameters are derived from past observed flow hydrographs available at the inlet and outlet of the studied reaches. Model simulations were compared and evaluated by applying a popular statistical measure to determine the degree of goodness of fit between observed and simulated hydrographs namely: the coefficient of determination. The obtained results reveal the appropriateness of the method for practical flood routing in the river channel. In terms of overall performance, the Muskingum method proved to be a simple and reliable method avoiding complicated mathematical and numerical computations for the case considered. The major advantage of the routing approach followed in this work is that no information on channel roughness and geometry are required to estimate the corresponding parameters.

***Key Words**:* Blue Nile, channel routing, hydrologic routing model, Muskingum method.

1. INTRODUCTION

The Blue Nile and its tributaries rise on the Ethiopian Plateau at a height of 2000 to 3000 meters above sea-level. The Blue Nile Basin, including Lake Tana and its basin, has an area of 324 530 km2, which extends from longitude 32.5ºE to 40ºE and latitude 8ºN to 15.5ºN (Fig. 1).

After crossing the Sudan frontier the Blue Nile flows for a distance of around 730 km till its point of junction with the White Nile at Khartoum. The river in the Sudan has an average gradient of about 1 in 10000 (Hurst, H.E. 1950).

The Blue Nile is a highly seasonal river, subjected to flooding events that cause severe damage along its course. Loss of property, damage to irrigation facilities and water services and the spread of water related diseases result from floods. During exceptional wet periods, the Blue Nile can give rise to large-scale flooding, particularly in the floodplain areas of Ethiopia and Sudan. The disaster in 1988 appeared to be the first of a series of high floods which struck the Sudan in 1994, 1996, 1998 and 1999. Floods are also of great benefits, such as: recharge of the groundwater aquifers, improve rainfed agriculture, enhance land fertility, flush sediment from rivers/reservoirs and reduce salinity in floodplain areas.

The Blue Nile contributes the largest volume of water to the Main Nile. At Khartoum its average flow for the period 1965-2000 is 25.5 x 109 m3 (August-September) falling to 0.6 x 109 m3 in March. During August and September the highest months on the Main Nile at Dongola the proportion contributed by the Blue Nile varies from 68 to 81% of the total flow. In 1988 the river at Eddeim exceeded its normal flow by around 34% on ten-day basis. The average record in the second period of

August was 682 x 106 m3/day while in a normal year 511 x 106 m3/day is recorded. The calculated percentage at Roseires, Sennar and Khartoum was 30%, 36% and 58% respectively (Mekawi, 2005).

The current work has explored the application of the Muskingum method to river flow routing in the Blue Nile during the flood season from July to September. The method is a commonly used hydrologic routing method for handling a variable discharge-storage relationship. Storage is linearly related to the inflow and outflow in the Muskingum method for flow routing in channels.

Tow reservoirs are located within the considered reach namely Roseires and Sennar. The two dams serve more than 1.05 x 1010 m2 of the Sudan irrigated area plus more than 90% of the total hydropower generation of the country. They are usually kept at their minimum operating level during the flood to allow the heavily silted water to pass to the downstream. Such an operation, which is intended to minimize reservoir siltation, limits the options to use these reservoirs for flood control and hydropower generation.

2. OBJECTIVE OF THE STUDY

Briefly this work aims to formulate a flood routing model for the Blue Nile using Muskingum method. The proposed model will be applied for the reach from Eddeim on the Ethiopian/Sudanese border to Khartoum where the confluence of the Blue and White Niles. It would enable the prediction of the daily flows at the downstream gauging sites along the river's water course during flood-time from July to September.

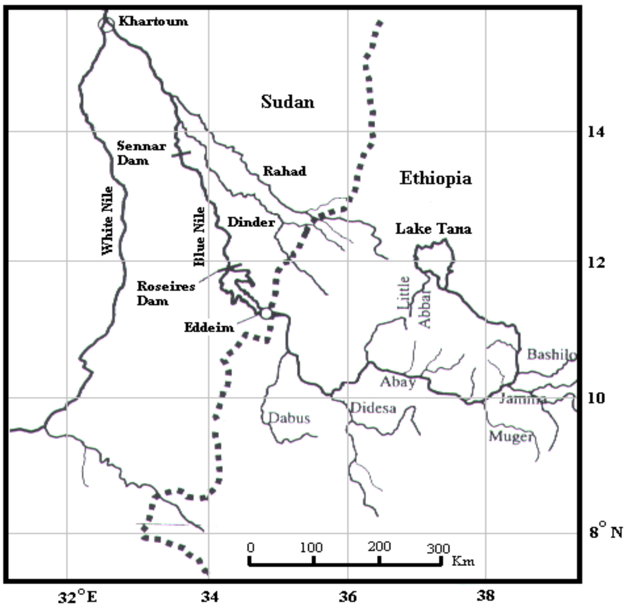

Figure 1: Location map

3. FLOOD ROUTING OF THE BLUE NILE

Flow routing is a procedure to determine the time and magnitude of flow (i.e., the flow hydrograph) at a point on a watercourse from known or assumed hydrographs at one or more points upstream. In a broad sense, flow routing may be considered as an analysis to trace the flow through a hydrologic system, given the input (Subramanya, K. 1994). The hydrologic analysis of problems such as flood forecasting, flood protection, reservoir design and spillway design invariably include flood routing. In these applications two broad categories of routing can be recognized.

1. Reservoir routing; and
2. Channel routing.

In channel routing the change in the shape of a hydrograph as it travels down a channel is studied. By considering a channel reach and an input hydrograph at the upstream end, this form of routing aims to predict the flood hydrograph at various sections of the reach. Information on the flood-peak attenuation and the duration of high-water levels obtained by channel routing is of utmost importance in flood-forecasting operations and flood-protection works.

A variety of routing methods are available and they can be broadly classified into two categories as follows:

- ✓ Hydrologic routing; and
- ✓ Hydraulic routing.

Hydrologic routing methods employ the equation of continuity while hydraulic methods employ the continuity equation together with the equation of motion of unsteady flow.

3.1. The Storage Equation

The passage of a flood hydrograph through a reservoir or a channel reach is an unsteady-flow phenomenon. It is classified in open channel hydraulics as gradually varied unsteady flow. The equation of continuity used in all hydrologic routing as the primary equation states that the difference between the inflow and outflow rate is equal to the rate of change of storage (Chow et al.).

For a hydrologic system, input I(t), output Q(t) and storage S(t) are related by the continuity equation as follows:

$$dS/dt = I(t) - Q(t) \qquad (1)$$

If the inflow hydrograph, I(t), is known, Eq. (1) cannot be solved directly to obtain the outflow hydrograph, Q(t), because both Q and S are unknown. A second relationship, or storage function, is needed to relate S, I, and Q; coupling the storage function with the continuity equation provides a solvable combination of two equations and two unknowns. The specific form of the storage function to be employed depends on the nature of the system being analyzed. The general form is as follows:

$$S = f(Q) \qquad (2)$$

Alternatively, in a small time interval Δt the difference between the total inflow volume and total outflow volume in a reach is equal to the change in storage in that reach.

$$\bar{I}\,\Delta t - \bar{Q}\,\Delta t = \Delta S \qquad (3)$$

Where:

$\bar{I}$ = average inflow in time Δt (m3/day);

$\bar{Q}$ = average outflow in time Δt (m3/day); and

Δ S = change in storage (m3).

By taking $\bar{I}$ = (I1 + I2)/2, $\bar{Q}$ = (Q1 + Q2)/2 and Δ S = S2 – S1 with suffixes 1 and 2 to denote the beginning and end of time interval Δt Eq. (3) is written as follows:

$$[(I_1 + I_2)/2]\,\Delta t - [(Q_1 + Q_2)/2]\,\Delta t = S_2 - S_1 \qquad (4)$$

3.2. Hydrologic Channel Routing

In reservoir routing, the storage is a unique function of the outflow discharge, S = f(Q). However, in channel routing the storage is a function of both outflow and inflow discharges and hence a different routing model is needed. The flow in a river during a flood belongs to the category of gradually varied unsteady flow. The water surface in a channel reach is not only not parallel to the channel bottom but also varies with time [Fig. (2)]. Considering a channel reach having a flood wave, the total volume in storage can be considered under two categories as follows: prism storage and wedge storage (Subramanya, K. 1994).

Prism storage
It is the volume that would exist if uniform flow occurred at the downstream depth, i.e. the volume formed by an imaginary plane parallel to the channel bottom drawn at the outflow section water surface.

Wedge storage
It is the wedge-like volume formed between the actual water surface profile and the top surface of the prism storage.

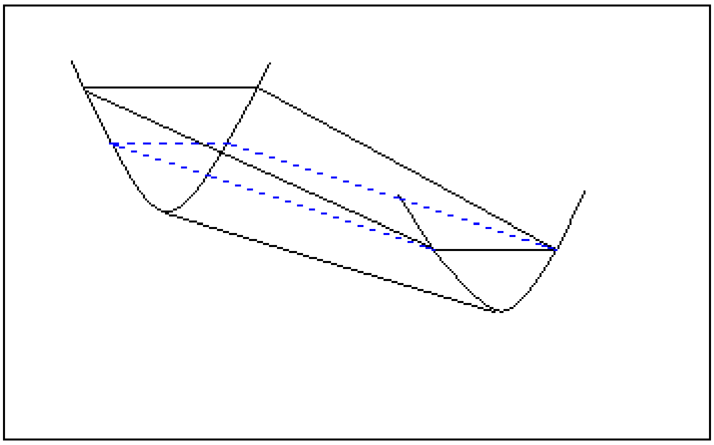

Figure 2: Storage in a channel reach

3.3. Muskingum Method

The most widely used method of hydrological stream routing is the Muskingum method originated by McCarthy (1938). This method models the storage volume of flooding in a river channel by a combination of wedge and prism storages. During the advance of a flood wave, inflow exceeds outflow, producing a wedge of storage. During the recession, outflow exceeds inflow, resulting in a negative wedge. In addition, there is a prism of storage which is formed by a volume of constant cross section along the length of prismatic channel.

Here is the routing equation for the Muskingum method:
$Qi+1 = C0Ii+1 + C1Ii + C2Qi$ (5)

Where:
$C0 = (-Kx + 0.5\Delta t) / (K - Kx + 0.5\Delta t)$
$C1 = (Kx + 0.5\Delta t) / (K - Kx + 0.5\Delta t)$
$C2 = (K - Kx + 0.5\Delta t) / (K - Kx + 0.5\Delta t)$
Note that $C0 + C1 + C2 = 1$.

Where:

K = a storage parameter that expresses the storage to discharge ratio (day)
x = weighting factor (which expresses the relative influence of the inflow and the outflow)
Δt = routing interval (day)
It has been found that for best results the routing interval Δt should be so chosen that $K > \Delta t > 2Kx$. If $\Delta t < 2Kx$, the coefficient C0 will be negative.

3.3.1 Travel Time along the Blue Nile

The travel time of flow from one point on a watershed to another can be deduced from the flow distance and velocity. The following table presents the approximate times of travels from a gauging site to the next along the Blue Nile as published in "The Nile Basin, vol. VII, 1946".

Table 1: Travel time along the Blue Nile (days)

Month	Khartoum	Sennar	Roseires	Eddeim
Jan. – Feb.	5 – 5.5	4 – 4.5	1.5 – 1.75	
Mar. – Apr.	6 – 6.5	5 – 5.5	2	
May – Jun.	6 – 5.5	5 – 4.5	2 – 1.75	
Jul. – Aug.	4.5 - 3	3.5 - 2	1.5 - 1	
Sep. – Oct.	2 – 2.5	1 – 1.5	0.5 – 0.75	
Nov. – Dec.	3.5 - 4	2.5 - 3	1 – 0.75	

3.3.2 Computations of Inflows to the Two Dams

To apply the Muskingum method to the first two reaches of the Blue Nile, from Eddeim to Roseires and from Roseires to Sennar, it was necessary to compute the inflows upstream of the two dams.

<u>Inflows to Roseires Dam</u>

It was definitely important to calculate the stored volumes of water in the Roseires reservoir. For the period from 1966 to 1984, this is achieved by using the storage volumes that given in the "Rules for the Operation and Maintenance of Roseires Dam and Sennar Dam" as approved by the MOIWR in 1968. Reservoir contents were also computed from the equations derived for the bathymetric surveys of 1985 and 1992 respectively. The 1985 survey was used for the period 1985-1991, while 1992 survey is used for the period 1992-2000.

Level (H), volume (V) relations for 1985 and 1992 are given by the following equation and the sets of parameters as in table (2).

V = c(H – 462)b (m3)

Table 2: Roseires reservoir level volume relation for 1985 survey

Level,H (m)	465-467.5	467.5-470.2	470.2-473.1	473.1-476.8	476.8-481
b	1.925	3.065	3.001	2.332	2.096
c	2.683	0.395	0.472	2.351	4.402
R^2	0.996	0.999	0.999	0.999	0.999

The inflows are basically computed by applying the general principle of inflow-outflow relationship as follows:
Change in storage (Δ S) = Inflow – Outflow – Evaporation Losses

<u>Inflows to Sennar Dam</u>
As in the case of Roseires dam, the same procedure is used to calculate the inflows to Sennar dam.

3.3.3 Calibration of the Model

The analysis was firstly concentrated on the determination of the basic coefficients of the Muskingum equation C0, C1 and C2. This has been carried out using the multiple regression option available in Excel program.

To obtain proper results, the available data is divided into three categories dry, normal and wet years depending on the ratio between the summation of the flows of July, August and September of the specific year and the corresponding average flow of the period under inspection. The years are considered as dry, wet and normal when the ratio is less than 0.95, more than 1.05 and falls between the two mentioned categories respectively.

<u>The Reach from Eddeim to Roseires</u>
For this reach, the flows at Eddeim gauging site are used as the inputs and the inflows to Roseires dam represent the outputs. The determination of the regression coefficients is firstly done year by year to enable the close inspection of the hydrographs during the flood time taking into account the magnitude of the flood. As it is necessary to get one set of parameters which fit to simulate the regime of the river along the considered reach, the flows of the dry, normal years in addition to years 1975, 1993 and 1994 were dealt with as one set to get the optimum parameters and the other high years with the rest of the years were used for verification purposes.

The resulting set of parameters is as shown below:

Coefficient	**C_0**	**C_1**	**C_2**	**R^2**
	0.31	0.34	0.35	0.97

It can be said that the influence of the flows which determine the outputs downstream of the reach mostly have the same weight.
By solving the equations of C_0, C_1 and C_2, the corresponding x and K values are estimated as follows:
x = 0.022; K = 1.06 days.

<u>The Reach from Roseires to Sennar</u>

For the following reach, the releases downstream of Roseires dam are used as the inputs and the inflows to Sennar dam represent the outputs. The data of twenty two years is treated as one set in order to get the appropriate set of coefficients which would enable the flood routing for the reach from Roseires to Sennar. The resulting set of parameters is as shown below:

Coefficient	**C_0**	**C_1**	**C_2**	**R^2**
	0.14	0.38	0.47	0.97

The corresponding x and K values are estimated as follows:
x = 0.140; K = 1.63 days.

<u>The Reach from Sennar to Khartoum</u>

The reach of the Blue Nile downstream of Sennar dam receives two tributaries namely Dinder and Rahad rivers.
Two scenarios are adopted for the analysis of this reach as follows:

- ✓ Using the releases downstream of Sennar dam as the only inputs;
- ✓ Taking the contribution of Dinder and Rahad rivers as additional inputs.

For the first scenario, the set of coefficients which fit to the calibrated data is determined as follows:

Coefficient	**C_0**	**C_1**	**C_2**	**R^2**
	-0.02	0.17	0.86	0.99

For the second scenario, the inputs are represented by the flows of Dinder and Rahad plus the releases downstream of Sennar dam as the mouths of the two rivers tend to be nearer to the upstream of the considered reach and the outputs are represented by the flows at Khartoum gauging site.
The obtained coefficients show that the estimated flows mainly are dependants on the flows recorded downstream of the reach.

One set of coefficients was determined to suit all of the calibrated years as follows:

Coefficient	**C_0**	**C_1**	**C_2**	**R^2**
	-0.02	0.17	0.86	0.99

Comparing the two sets, it is obvious that the contribution of the two tributaries does not have a significant effect on the routing of the flows at Khartoum. The corresponding x and K values which are computed from these coefficients are as follows:
x = 0.093; K = 7.15 days.

3.3.4 Verification of the Model

It is essential to ensure the applicability of this method to the three reaches of the Blue Nile under inspection. A popular statistical parameter is calculated to describe the goodness of fit of the model namely the coefficient of determination (R2).

The Reach from Eddeim to Roseires

The table (3) gives the obtained values of the coefficient of determination (R^2) calculated for the selected years to verify the suitability of the model to the considered reach.

Table 3: Goodness of fit of the model of the 1st reach

Year	R^2	Year	R^2
Wet Years		**Dry Years**	
1969	0.93	1968	0.85
1970	0.91	1972	0.94
1974	0.93	1986	0.96
1977	0.95	1989	0.96
1985	0.98	1990	0.97
1996	0.96		
1998	0.94		
1999	0.96		
2000	0.92		

The Reach from Roseires to Sennar

The table (4) gives the obtained values of the coefficient of correlation (R^2) calculated for the selected years to verify the suitability of the model to the considered reach.

Table 4: Goodness of fit of the model of the 2nd reach

Year	R^2
1975	0.98
1982	0.95
1988	0.96
1995	0.96
1998	0.97

The Reach from Sennar to Khartoum

The table (5) gives the obtained values of the coefficient of correlation (R^2) calculated for the selected years to verify the suitability of the model to the considered reach.

Table 5: Goodness of fit of the model of the 3rd reach

Year	R^2
1968	0.92
1969	0.97
1974	0.93
1979	0.92
1980	0.95
1981	0.93
1987	0.95
1994	0.98
1998	0.99

The figures (3,5,7) give examples of the simulated flows at Roseires, Sennar and Khartoum for the years 1998, 1988 and 1994 respectively while the figures (4,6,8) review the simulated flows of the corresponding verification periods at the mentioned sites.

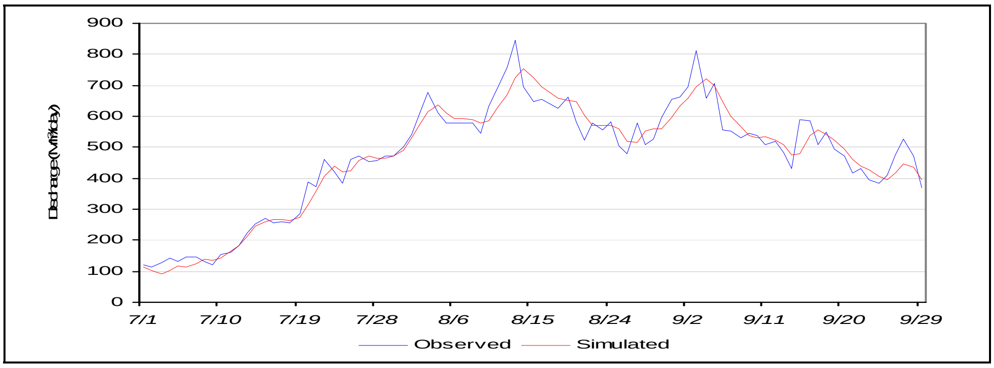

Figure 3: Simulated flows at upstream of Roseires dam (Year 1998)

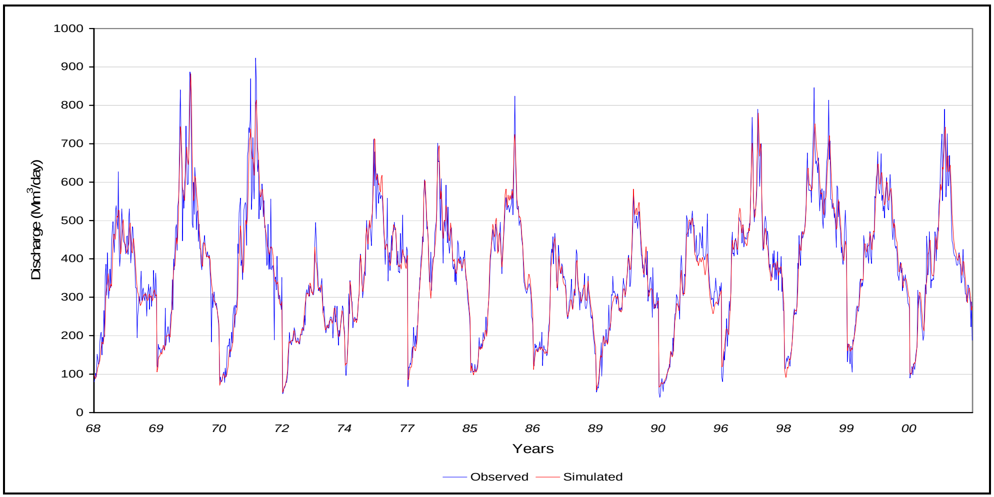

Figure 4: Observed and simulated flows at upstream of Roseires dam

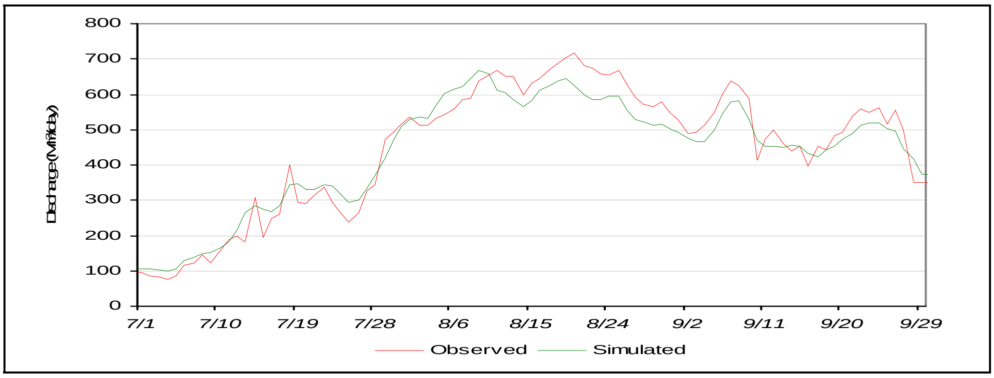

Figure 5: Simulated flows at upstream of Sennar dam (Year 1988)

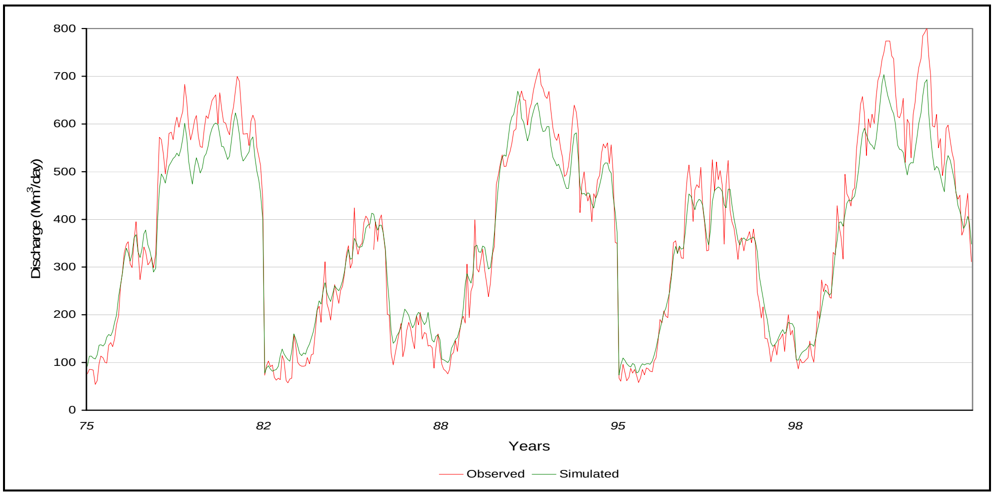

Figure 6: Observed and simulated flows at upstream of Sennar dam

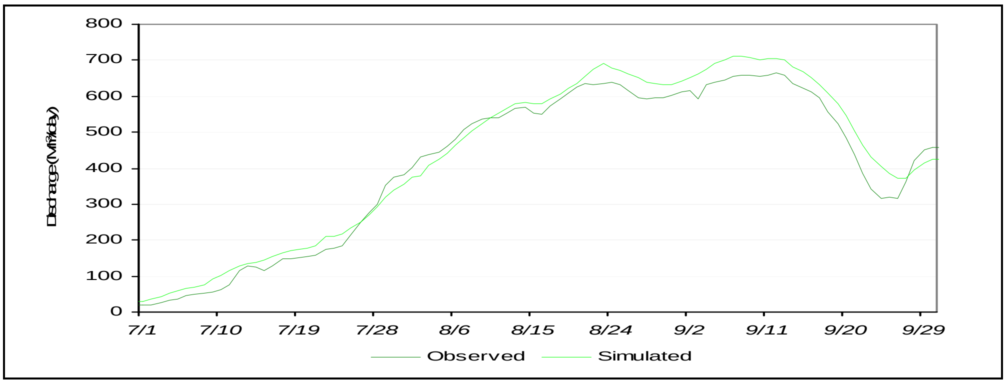

Figure 7: Simulated flows at Khartoum (Year 1994)

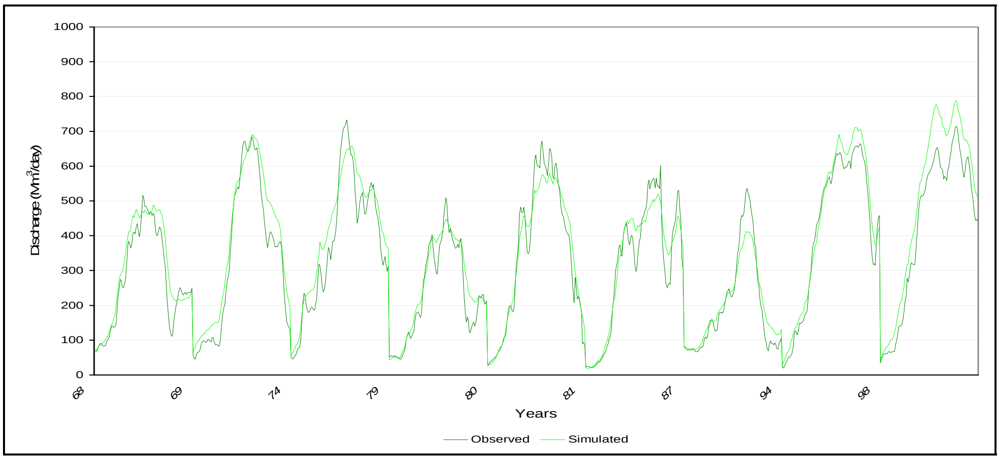

Figure 8: Observed and simulated flows at Khartoum

4. RESULTS AND DISCUSSIONS

Here are some of the comments concerning the application of the Muskingum method for the flood routing of the Blue Nile.

The First Reach

For the reach from Eddeim gauging site to Roseires dam, the values of the coefficient of determination (R2) for the verified years are in the order of more than 0.91 in exception of year 1968 which has a R2 value equal to 0.85. These results seem to be promising and the determined coefficients manage to simulate the target flows in a proper way as shown in the given figures.

The determined values of x and K are estimated at 0.022 and 1.10 days respectively. Particularly the value of K is in agreement with the actual case during flood time as the flood wave needs on average one day from Eddeim to Roseires.

The flood routing of this reach should consider the following points:

- ✓ The flows at the upstream of Roseires dam are directly affected by the natural flows at the upstream gauging site i.e. Eddeim.
- ✓ No significant influence of the storage on the calculated flows upstream of the dam for the period July till mid September and it is only marked late in the last week or two weeks of September.
- ✓ The effect of the evaporation can be ignored during the wet season and its amount bears no relation to the volume of flows during the high season.
- ✓ The contribution of the local inflows to the river during the rainy season should also be taken into consideration.

The Second Reach

For the second reach from Roseires to Sennar five years are subjected to be examined for the evaluation of the model's performance. The coefficient of determination (R2) has values higher than 0.95. Years 1975, 1988 and 1998 as representative years of high floods have shown very good results. However the simulated high flows tend to be underestimated within 10%. The determined values of x and K are equal to 0.140 and 1.60 days respectively. The obtained value of K represents exactly the time needed by a flood wave from Roseires to Sennar.

The flood routing of the present reach can be better understood by considering the following points:

- ✓ The flows at Sennar follow the same pattern of those released downstream of Roseires dam as the two dams share the same regulation rules and are operated in absolute cooperation.
- ✓ As in the case of Roseires dam, the inflows to Sennar dam are not affected by the storage operation before mid of September.
- ✓ The evaporation is very small in comparison with the flows in the river channel so that it has no influence on the inflows upstream of the dam.
- ✓ A distance of 270 km between the two dams may affect on the precision of the determination of the routing parameters.
- ✓ The contribution of the runoff during the rainy season should also be taken into account.

The Third Reach

According to the third reach the obtained values of the coefficient of determination are higher than 0.90. The corresponding values of x and K are 0.093 and around 7 days respectively.
It was obvious that some of the simulated flows at Khartoum have appeared to be higher than the observed ones. On the other hand, the calculated value of K is too high and does not represent the case in the reality. It is almost double of the real estimated travel time of a flood wave from Sennar to Khartoum. This can be attributed to he attenuation effect along this reach.

For the flood routing of the Blue Nile from Sennar to Khartoum the following points draw attention:

- ✓ The contribution of the Dinder and Rahad rivers does not play a marked role concerning the routing of the flows at Khartoum as it has been proved by the two adopted scenarios, although their daily contribution ranges on average from 10% to 18% of the amount of flow at Sennar.
- ✓ The two scenarios have shown the same results concerning their performances.

Another factor should be taken into account concerning this reach. It is the distance between the two gauging sites. The risk site i.e. Khartoum is located 350 km far from the upstream gauging site i.e. Sennar which may probably be unrepresentative of the flows to be expected at Khartoum. On the other hand, the attenuating effect of the flood plain storage throughout the reach may explain the tendency of the simulated flows to be overestimated.

5. CONCLUSION AND RECOMMENDATIONS

The Blue Nile is treated as three separated reaches. The obtained results regarding this task are promising as the model parameters successfully managed to simulate the flows of the Blue Nile at the selected gauging sites with a relatively acceptable standard of accuracy.

For the first reach from Eddeim to Roseires, the obtained results are more promising than those of the other two reaches. It is important to mention that for the second reach the simulated flows at Sennar were underestimated and this can be attributed to the contribution of the lateral inflows.

For the third reach, the simulated flows at Khartoum were overestimated. This can be attributed to the following factors:

- ✓ The data at Khartoum is to some extent uncertain as proved by comparison with well known sources. The limited number of flow measurements throughout of the year lead to poor rating curves.
- ✓ The attenuation effect along the considered reach. The low value of the weighting factor x ensures this fact.
- ✓ The actual travel time of a flood wave is on average three days so this somehow means that the flows at the upstream gauging site are not representative of the flows to be expected at downstream of the reach.

The Muskingum method has managed to reproduce the observed flood hydrographs and the obtained results reveal the appropriateness of the method for practical flood routing in the Blue Nile.

The following recommendations can be drawn:

- ✓ The existence of a validated and reliable data base of the Blue Nile system is vital.
- ✓ Improvement in data collection methods in terms of accuracy and frequency.
- ✓ Accurate measurements are not only required at gauging sites of the network but also for the runoff generated by seasonal streams draining to the river during heavy rainfall events.
- ✓ The obtained results of the routing model show that it is suitable to be applied for the reach under consideration. Therefore, it is recommended to be used for the flood routing of the Blue Nile.

The advantage of this method is that it is simple to be understood, easy to be programmed, and generally successful in finding the best estimates of the parameters. Channel geometry does not need to be defined in detail. There is no requirement to assess roughness coefficients throughout the reach.
This routing is also adequate for planning when the flows remain within the range of historical records.

- ✓ More refinement work is highly recommended for the present routing model. On the other hand, dealing with the current Muskingum's coefficients within flexible range (±5%) would give good results.

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AUTHOR BIOGRAPHY

Amira A. A. Mekawi works as research Engineer at the Hydraulics Research Station (HRS) of the Ministry of Irrigation and Water Resources, Sudan. She obtained her M Sc in water resources management at Lueneburg University, Germany in 2005, under the sponsorship of the DAAD. Currently she is a PhD student at the University of Gezira, Sudan. Her major interests include hydrology and water resources issues. She can be reached at hrs_amira@hotmail.com