Investigation of Step Trends of the Nile River Flow Time Series

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Abstract
Having long-term daily-observed flow data of 44 years (1965-2009) makes a unique opportunity to study the hydrological changes on the Nile basin due to land use changes, upstream water usage, and climate change, and to know their impacts on the Nile River flow. In this study, the annual flow time series (TS), based on hydrological year (June- May), were analyzed and checked for the absence of step trends using two statistical software: Freq (Zhou, 1992) and Spell-Stat (Agor and Librada, 2005). Similar results were obtained.
Flow TS of the Nile, Blue Nile, and White Nile were analyzed for the flow observed at Dongola, Eddeim (often written el Deim) and Khartoum, and Malakal stations, respectively. All flow TS were tested for the absence of step trends by checking the TS for the stability of the mean and the stability of the variance at 95% confidence level.
Pettitt test (change point test) was used to identify the possible step trends in the TS under consideration. TS were checked for the absence of step trends for the probability higher than 0.8.
Results show that since 1987/1988, the Blue Nile flow has increased significantly, as observed at Eddeim and Khartoum. For both Eddeim and Khartoum stations, the mean flow of the TS for the period from 1965/1966 to 1986/1987 is statistical lower than the mean flow of the TS for the period from 1987/1988 to 2008/2009. The flow increase after 1987/1988 creates step trend in the flow TS at Eddeim and Khartoum. Flow TS at Eddeim and Khartoum were found to be both stable in the variance. It is worth to mention that in 1988, Sudan had experienced huge and devastating flood (Sutcliffe et al. 1989).
On the contrary, the White Nile flow has decreased, as observed at Malakal. Since 1972/1973, the flow has dropped significantly making the TS not stable in the mean. However, the flow TS is stable in the variance.
Finally, the Nile flow TS, as observed at Dongola, was found to be stable in both the mean and the variance, i.e., there is no step trend in the TS. Results also show that there are high correlations between the stations on the Nile and the stations on the Blue Nile on one side and the stations on the Attbra River on the other side, and a weak correlation between the stations on the Nile and the stations on the White Nile. This indicates the strong influence of the Blue Nile and Attbra River flows on the Nile flows. The implications of this study are for climate change studies, for water management and planning, and for early warning systems.

***Key words*:** Nile River, Blue Nile, White Nile, flow time series, step trends

1. INTRODUCTION

The Nile River and its tributaries are the major and most important surface water resources in Sudan. Most part of its water resources is from the Ethiopian plateau and the equatorial lakes, and some part is from the rainfall over the Nile basin inside Sudan. The rain falls over the Ethiopian plateau twice per year: The short rainy season which starts at the mid of March and ends at the end of May, and the long rainy season which starts at the second half of June and ends at the second half of September.

The Ethiopian plateau is high and have sharp decline towards Sudan lands, which makes its rivers (Blue Nile and its tributaries Dinder and Rahad, River Attbara and Sobat River) are direct reflect to the rainfall and consequently the basic source of the floods, where the most inflow of the Blue Nile and Attbara River is in the period from May – October and they are the important source of the sediment in the reservoirs and main canals.

The annual inflow of the three rivers is about 85% of the normal total inflow of the Nile. The Blue Nile and its tributaries (Dinder and Rahad) is the main and important source of the floods, and its inflow at the flood period is about 66% from the total inflow of the Nile at the flood period. While the inflows of the White Nile at Malakal (Sobat and Bahr elgabal), and the Attbra River during flood is 15% and 19% of the total inflow of the Nile at the flood period, respectively.

At the equatorial plateau the rain falls more or less around the whole year (April – November) and it is the main source of Bahr el Jabel flow which looses half of its inflow at the swamps region in southern Sudan. Downstream the swamps, just after the conjunction with Sobat River, the White Nile starts.

To investigate the climate change vulnerability on the Nile, for better water planning and management, and for early warning systems, the Nile River flow TS has been tested for the absence of step trends. In addition, the correlations between the stations that are used in flood forecast were also carried (See Fig.1).

The investigation has been done using the long-term daily-observed flow data of 44 years (1965/1966-2008/2009). The key stations that have been used for investigating the absence of step trends are Eddeim and Khartoum on the Blue Nile, Malakal on the White Nile, and Dongola on the Main Nile.

Figure 1: Sudan hydrological network

2. METHODOLOGY

The procedure and test applied in this study are as follow:

a) Visual check of data consistency

b) The annual flow TS, based on hydrological year (June-May), of the key stations in the study area: Eddeim, Khartoum, Malakal, and Dongola were analyzed for step trend analyses.

c) The correlations between stations were carried out using long-term daily-observed flow data.

d) Two statistical software: Freq (Zhou, 1992) and Spell-Stat (Agor and Librada, 2005) were used to analyze TS for:

1) Pettitt test (Change point test)
2) Test for the stability of the variance
3) Test for the stability of the mean

The change point test is used to determine at what time there is possible change in the TS. Once the possible change point is identified, the TS is split at that point. Then, the test for the stability of the variance and the test for the stability of the mean will be applied by splitting the TS at the predefined change point.

The test of the stability of the variance computes the ratio of the variances of two split, non-overlapping subsets of the TS. The distribution of the variance ratio from the normal distribution is known as F or Fisher distribution. Similarly, the t-test, which has Student's t-distribution, is computed for the stability of the mean. The test computes and compares the means of the two split, non-overlapping subsets of the TS (same subsets used for the stability of the variance). For more details about these tests see Agor, 2003; Dahmen and Hall, 1990; Bushara, 2007.

3. RESULTS AND DISCUSSIONS

In this study, the flow TS were checked for the absence of step trends using annual flows based on hydrological year (June-May). The annual flows were computed from the observed daily flows. Pettitt test (Fig. 2) was used to identify possible step trends in the flow TS for the Blue Nile, White Nile, and Nile River. The probability higher than 0.8 is considered statistically significant (Agor, 2003), and the flow TS are checked for the absence of step trends only if the probability is higher than 0.8. Pettitt test suggests that there are possible step trends for flow at Eddeim, Khartoum, Malakal, and Dongola after the hydrological year 1987/1988, 1987/1988, 1972/1973, and 1979/1980, respectively. The results of step trend analyses are summarized in table 1 and presented in figures 3 and 5. The trends analyses were carried out at 95% confidence level.

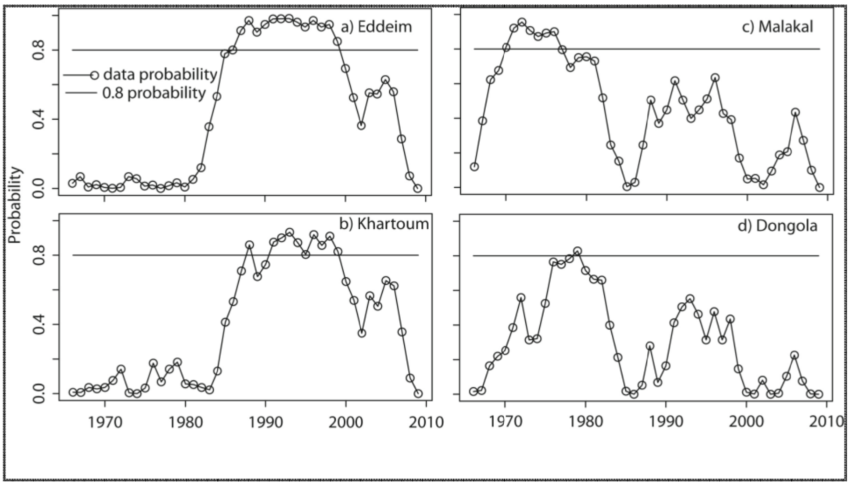


Figure 2: Pettitt test for: a) Eddeim, b) Khartoum, c) Malakal and d) Dongola stations

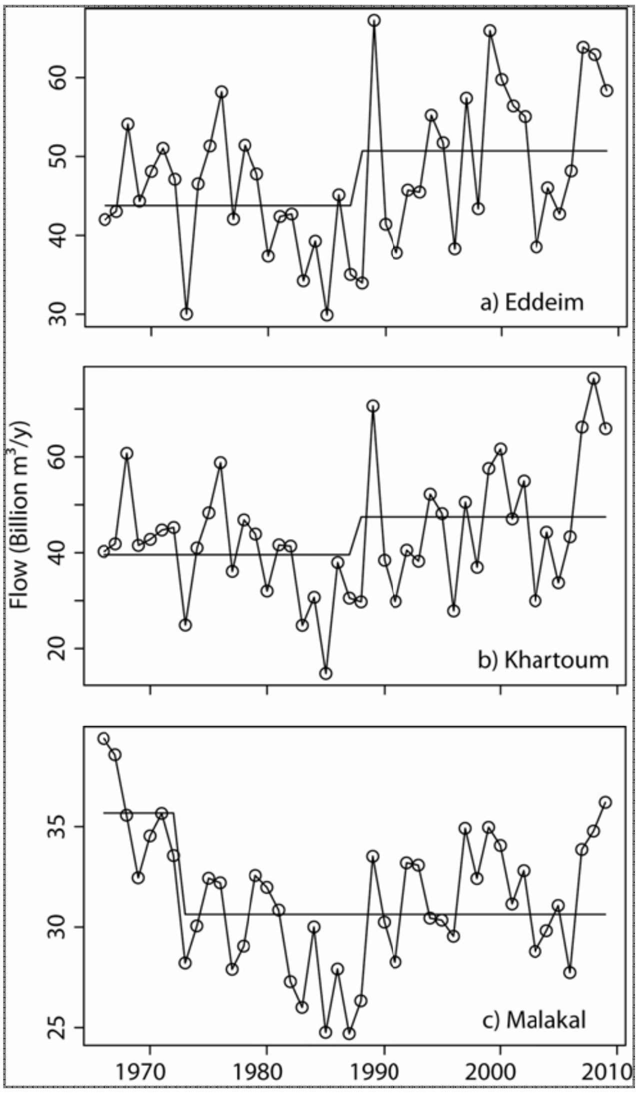


Figure 3: Step trends for: a) Eddeim, b) Khartoum and c) Malakal stations

Table 1: Step trend analyses

Station	Data subsets For hydrological year	F-test	t-test	(Mean annual flow (Billion m^3/year)*
Eddeim	1965/1966 to 1986/1987 and 1987/1988 to 2008/2009	0.415 < 1.83< 2.409 True, TS is stable in the variance	-2.018 < 2.589 < 2.018 False, TS is not stable in the mean	47.2416
Khartoum	1965/1966 to 1986/1987 and 1987/1988 to 2008/2009	0.415 < 1.848 < 2.409 True, TS is stable in the variance	-2.018 < 2.077 < 2.018 False, TS is not stable in the mean	43.5299
Malakal	1965/1966 to 1971/1972 and 1972/1973 to 2008/2009	0.199 <1.36 < 2.409 True, TS is stable in the variance	-2.018 < 4.233 < 2.018 False, TS is not stable in the mean	31.4369
Dongola	1965/1966 to 1978/1979 and 1979/1980 to 2008/2009	0.351 < 2.061< 2.39 True, TS is stable in the variance	-2.018 < 1.595 < 2.018 True, TS is stable in the mean	71.999

***** For mean flow the whole dataset is used.

Since 1987/1988, the flow of the Blue Nile has increased significantly as observed at Eddeim and Khartoum stations (Fig. 3a and 3b). The means of flow before and after 1987/1988 are significantly different at 95% confidence level. Difference in means causing instability of the mean for the TS, and the TS at Eddeim and Khartoum exhibit step trend in this year. The flow TS of the Blue Nile were found to be stable in the variance but not in the mean, as mentioned.

The minimum and maximum annual observed flow at Eddeim is 29.902 Mm3, and 67.2586 Mm3, respectively. The minimum and maximum flows occurred in 1984/1985 and 1988/1989, respectively. Similarly, the minimum and maximum annual observed flow at Khartoum is 14.807 Mm3, and 76.3574 Mm3, respectively, and were occurred in 1984/1985 and 1988/1989, respectively. The average annual flow of the Blue Nile observed at Eddeim and Khartoum is 47.2416 Mm3 and 43.5299 Mm3, respectively. It has to mention that in 1988 Sudan had experienced huge and devastating flood (Sutcliffe et al. 1989).

On the contrary, for the White Nile flow, the analysis showed that there is statistically significant flow reduction after 1972/1973 causing step trend in the TS (Fig. 3c). The flow TS is stable in the variance but not in the mean. It has to be mentioned that only few data-points are used for the split record test (Pettitt test), and that constrains making solid judgment about the presence of step trend after 1972/1973. However, there is no doubt about the flow decrease of the White Nile. Bushara and Mekawi, 2009, used data from 1965 to 2000, have found an annual flow reduction of about 97.43 Mm3. The mean annual flow of the White Nile observed at Malakal is about 31.4369 Mm3. The minimum and maximum annual observed flow at Malakal is 24.7009 Mm3, and 39.3775 Mm3, respectively, and were occurred in 1984/1985 and 1965/1966, respectively. The max flow had occurred when the water level of Lake Victoria is very high (Fig. 4). As the water levels of the lake are declining (Fig. 4), the White Nile flow declines too, this suggests the strong control of Lake Victoria on the White Nile flow.

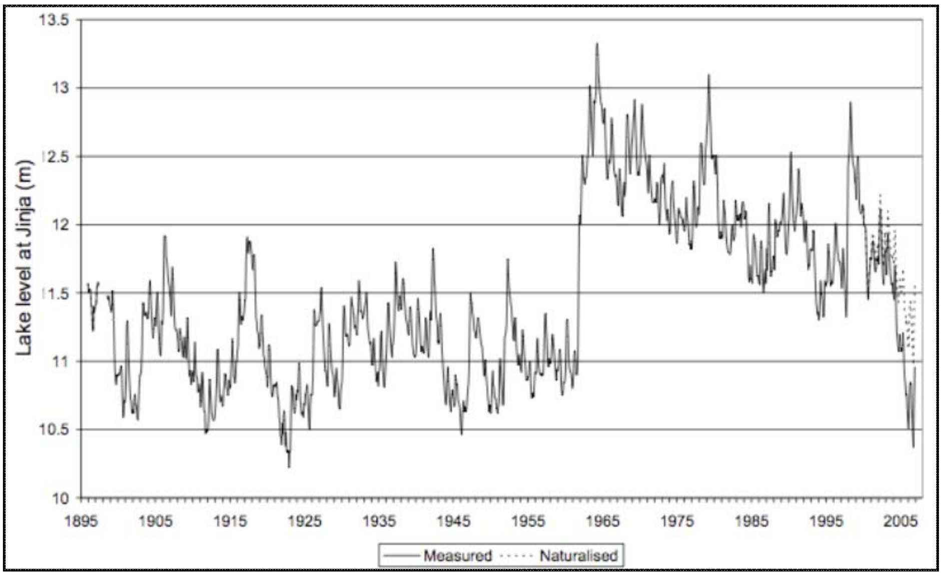


Figure 4: Lake Victoria, monthly measured levels- 1896-2006, ***after Sutcliffe and Petersen, 2007***

In this study, the flow TS of the Attbra River is not analyzed, but Bushara and Mekawi, 2009 have found that the Attbra River flow is increasing with an annual amount of about 615.65 Mm3, using data from 1986 to 2000, and they did not observe step trend in the TS. As the step trends are more likely due to the clime change effect, and as the climate change effects occur gradually, therefore, the exact location of the step trends could be slightly shifted.

The flow TS of the Nile, as observed at Dongola, showed to be stable in both the mean and the variance, i.e. there is no step trend in the Nile River flows (see Fig. 5). As the Blue Nile, and Attbra River flows increase, and as the White Nile flow decreases, and as the Nile River flow fairly remains constant, this implies fixed amount of water used within the Sudan, and implies that the decrease of the White Nile flow is counterbalanced by the increase of the Blue Nile and Attbra River flows. The flow reduction of the White Nile could be due to the effect of climate change, as more water evaporated from the East African lakes and the swamps in the southern Sudan. And it seems that the evaporated water from the White Nile basin falls as precipitation over the Blue Nile basin, causing an increase of the Blue Nile flows. However, the total amount of water remains fairly constant, as there is no step trend in the Nile flows. Therefore, detailed climatological studies are recommended to confirm these findings.

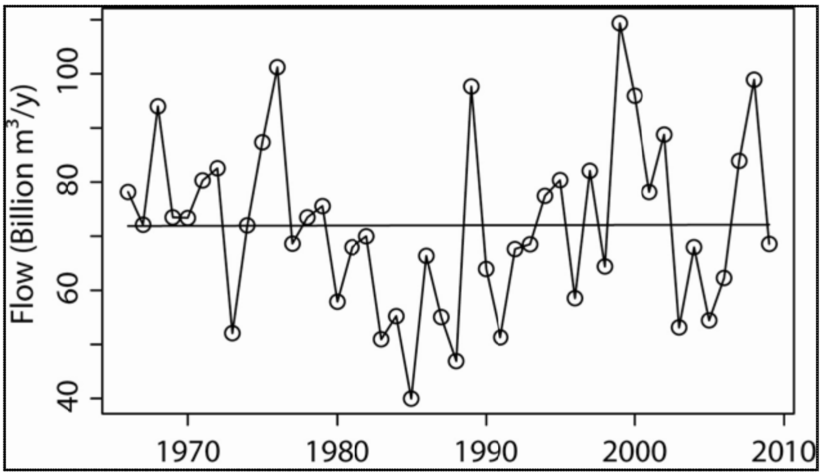


Figure 5: Flow TS and the mean flow at Dongola station

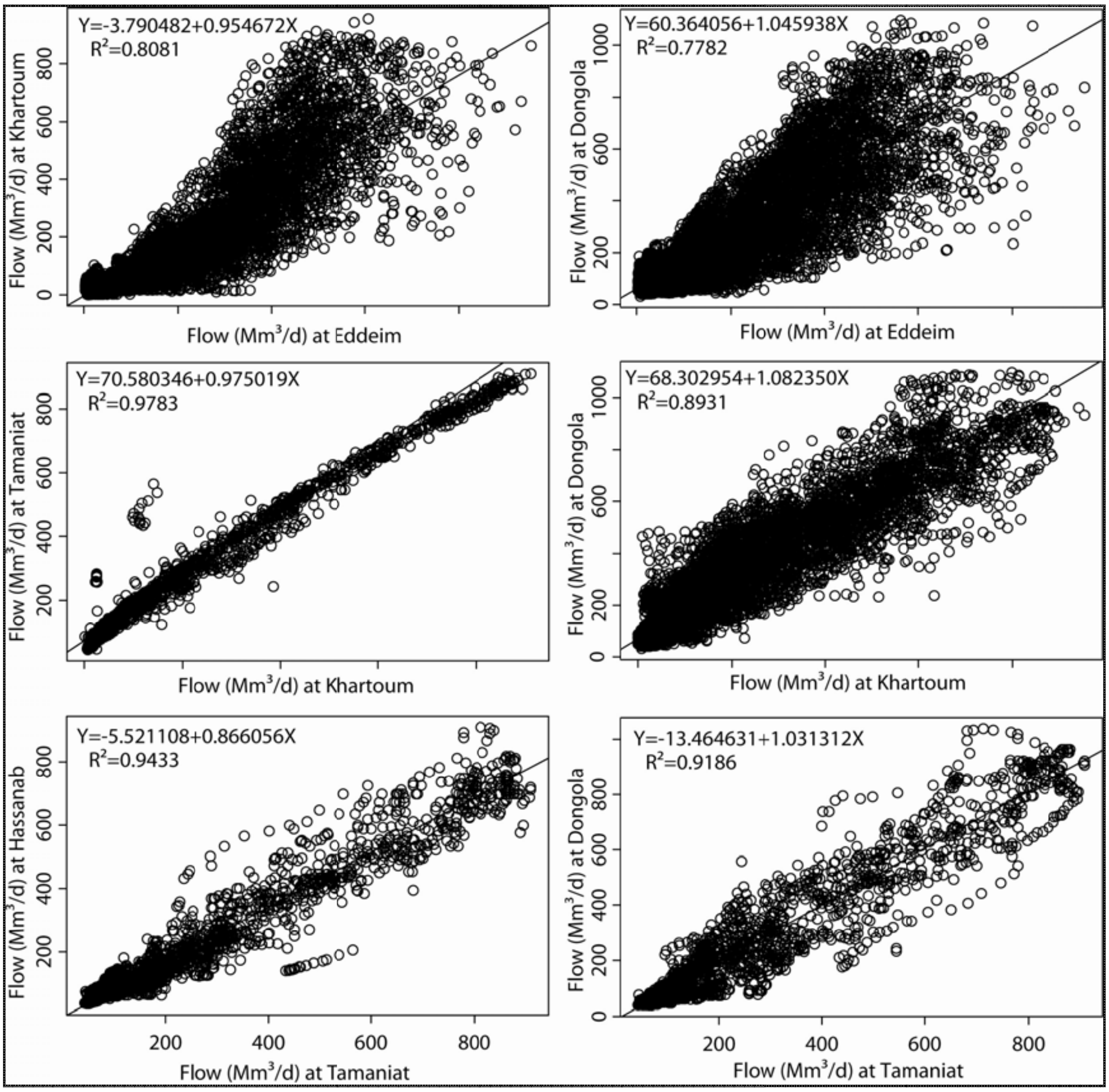
Figure 6 shows the correlation between measuring stations using daily observed flow data for the period from 1965 to 2009 for the stations: Eddeim, Khartoum, Malakal, and Dongola, and for the period from 2000 to 2009 for the stations: Tamaniat, Khasm El Girba, Jebel Aulia, and Hassanab. The figure shows that there are high correlations between the stations on the Nile River (Tamaniat, Hassanab, and Dongola), and high correlations between the stations on the Nile River and the stations on the Blue Nile (Eddeim and Khartoum). The correlation coefficient between all the above stations varies between 0.989 and 0.882, which is very high correlation.

The correlation between Dongola and Khashm El Girba is 0.8039, which is also high. It has to be mentioned that the Attbra River is a seasonal river and Khashm El Girba is a flow measuring station on the Attbra River. The high correlations between the stations on the Blue Nile and the stations on the Nile River indicate the strong control of the Blue Nile on the Nile River flow. Similarly, the high correlation between Dongola and Khashm El Girba indicates that the Nile flow is controlled by the Attbra River flow to some extent during the flow of the Attbra River.

The correlation between Khartoum and Eddeim is affected by evaporations from Roseires and Sennar dams, abstractions, rainfall runoff to the river, Rahad and Dinder flows, and transmission losses in the river reach.

On the other hand, the correlations between the stations on the Nile River and the stations on the White Nile vary from no correlation (correlation coefficient = 0.0276) to weak correlation (correlation coefficient =0.459). The weak correlations between the stations on the Nile and the stations on the White Nile indicate the little control of the White Nile on the Nile River flow.

Our findings are consistent with the Ministry of Irrigation and Water Resources, 2009, findings (see Fig. 7), which shows the control of the Blue Nile and Attbra River on the Nile flow, and the Nile flow is less controlled by the White Nile. The White Nile represents the base flow of the Nile, while the Blue Nile and Attbra River represent the flood flows of the Nile.


Y=-3.790482+0.954672X
R^2=0.8081
Flow (Mm³/d) at Khartoum
Flow (Mm³/d) at Eddeim
Y=60.364056+1.045938X
R^2=0.7782
Flow (Mm³/d) at Dongola
Flow (Mm³/d) at Eddeim
Y=70.580346+0.975019X
R^2=0.9783
Flow (Mm³/d) at Tamaniat
Flow (Mm³/d) at Khartoum
Y=68.302954+1.082350X
R^2=0.8931
Flow (Mm³/d) at Dongola
Flow (Mm³/d) at Khartoum
Y=-5.521108+0.866056X
R^2=0.9433
Flow (Mm³/d) at Hassanab
Flow (Mm³/d) at Tamaniat
Y=-13.464631+1.031312X
R^2=0.9186
Flow (Mm³/d) at Dongola
Flow (Mm³/d) at Tamaniat

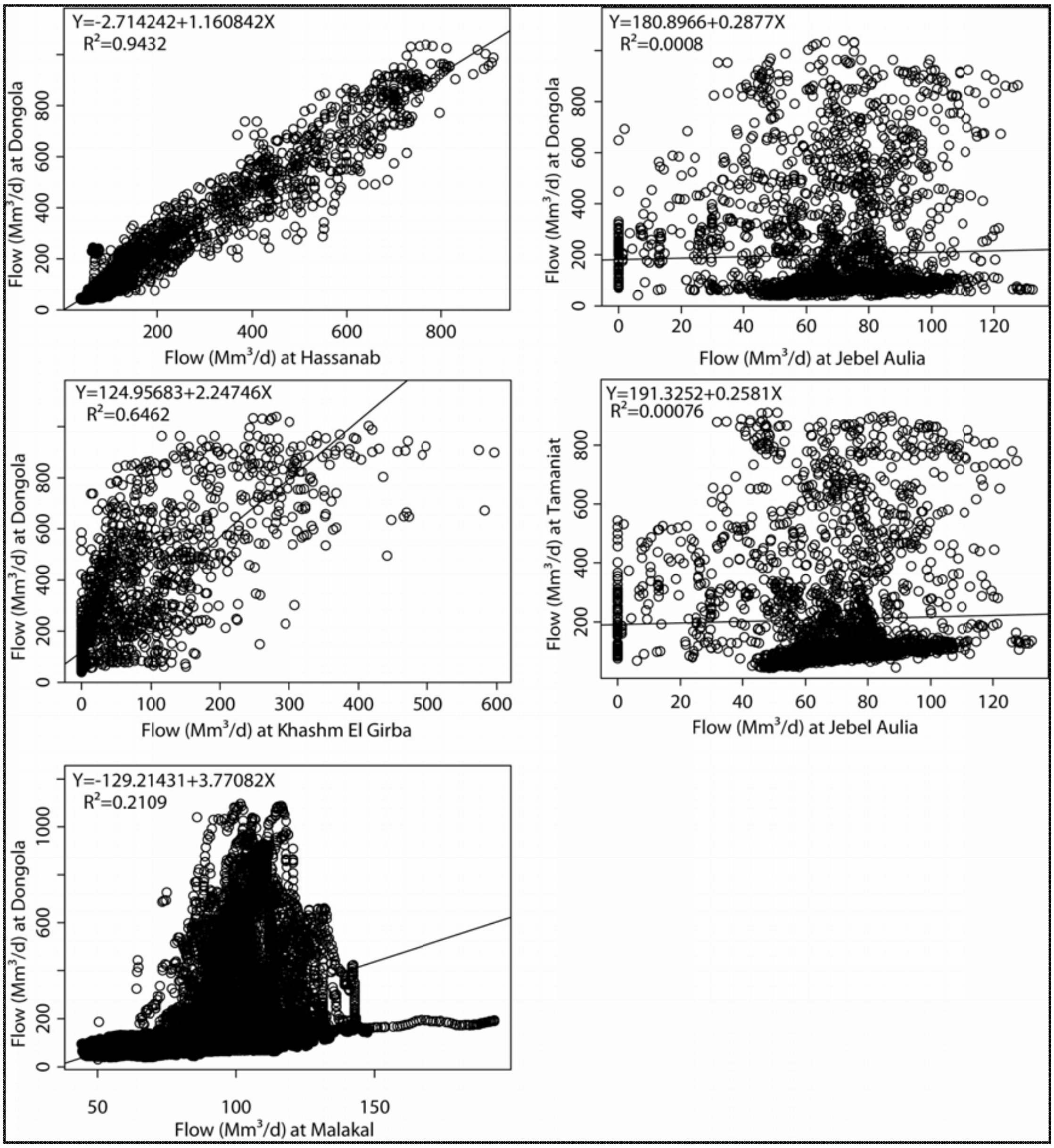


Figure 6: Daily observed flow correlation between stations

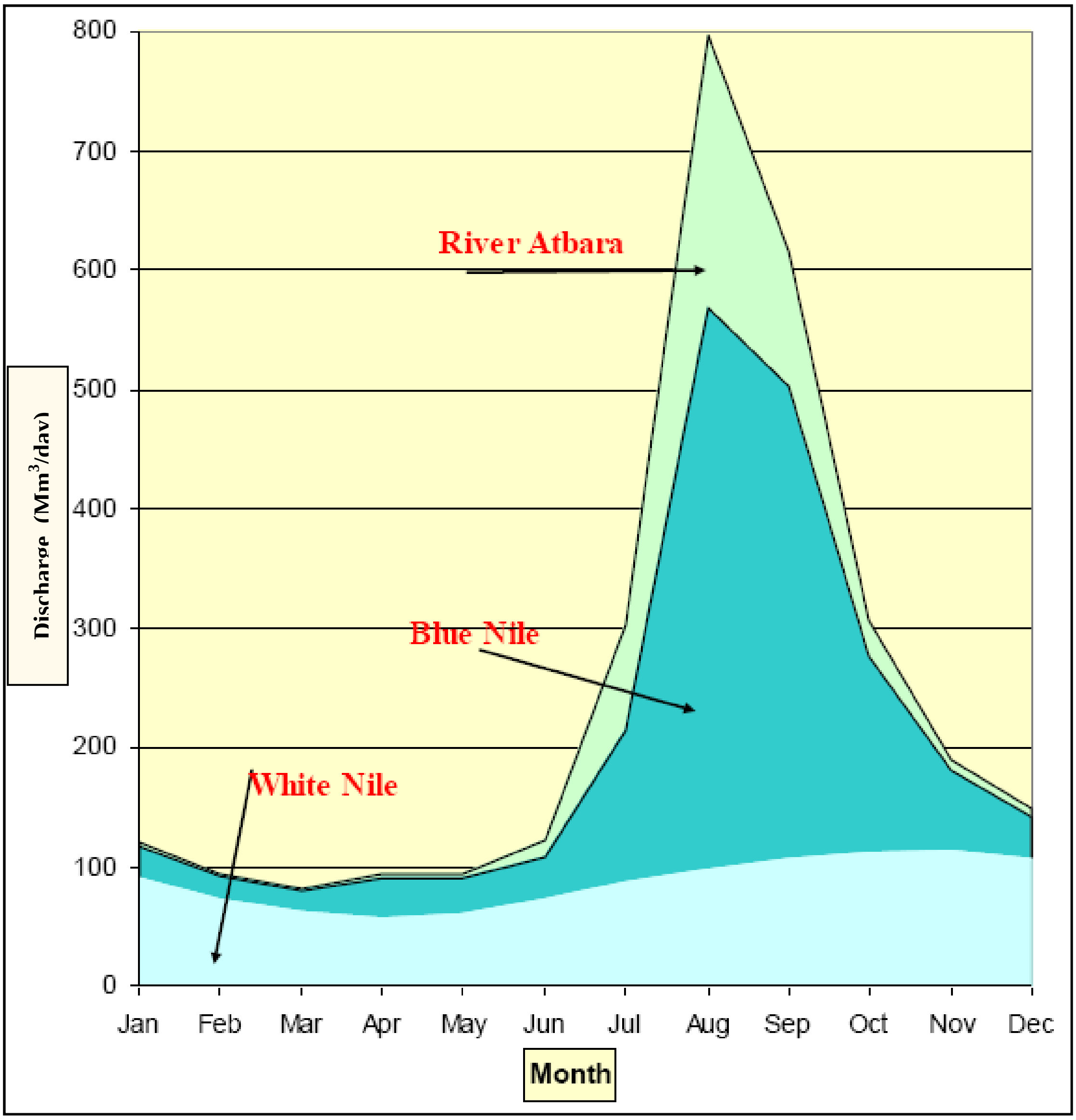


Figure 7: Long-term (1965-2008) flow hydrograph of the Nile and its main tributaries within the Sudan, the source is the Ministry of Irrigation and Water Resources, Nile Water Directorate, flood report 2009.

4. CONCLUSION

In this study, we investigated the absence of step trends in the Nile River flow TS, using daily-observed flow data of 44 years (1965-2009). The data were analysed based on hydrological year (June-May). The main findings of our study are as follow:

1) The Blue Nile flow TS were found to be stable in the variance but not in the mean, i.e. there is step trend. Since 1988, the Blue Nile flows have increased significantly, as observed at Eddeim and Khartoum flow measuring stations.
2) The White Nile flow TS were found to be also stable in the variance but not in the mean, i.e. there is step trend. Since 1973, the White Nile flows have decreased significantly, as observed at Malakal measuring station.
3) The Nile flow TS were found to be stable in both the variance and the mean, i.e. there is no step trend. The Nile flow TS were analyzed for the flow observed at Dongola.
4) To understand the link between the upstream and downstream flow stations, and to check data consistency, correlation between stations are carried out. Results shows strong correlation

between the stations on the Nile and the stations on the Blue Nile on one side and the stations on the Attbra River on the other side. There is weak correlation between the stations on the White Nile and the stations on the Nile. This indicates the strong control of the Blue Nile and Attbra River, and less control of the White Nile on the Nile River.

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