Sediment Balance in the Blue Nile in Sudan

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ABSTRACT

The Blue Nile is one of the two main tributaries of the Nile River. It originates in the Ethiopian Plateau. The Blue Nile water plays an important role in the economic development of Sudan in terms of irrigated agricultural development and hydropower generation. The average annual flow of the Blue Nile is 50 billion cubic meters, 80% of it occurs during the flood season (July – October). During the flood season the river brings down large amounts of sediment estimated as 146 million tons per year. The sediment material originates mainly from heavy erosion in the upper catchment area in Ethiopia. The Blue Nile system within Sudan includes two reservoirs, Roseires and Sennar, and two tributaries, viz. Dinder and Rahad. Sennar and Roseires reservoirs have already lost 65% and 34% of their initial storage capacities due to sedimentation, respectively. The Blue Nile sediment in Sudan is monitored at a number of stations scattered along its length. The sediment concentrations vary during the flood season and from year to year. The sediment load is also variable along the river length due to deposition in the river channel, trapping in the reservoirs, diversion to irrigated schemes and inputs from tributaries. In this paper the sediment trap efficiency of each reservoir is calculated using bathymetric survey data. The current trap efficiency of Roseires and Sennar reservoirs is found to be 17% and 5%, respectively. The average annual sediment diverted to Gezira Scheme is $8.5x10^6$ tons. The spatial sediment distribution along the Blue Nile is given at key river nodes. Upstream and downstream each reservoir and at Gezira canals' off-takes and at its confluence with the White Nile. The annual average sediment contribution of the Blue Nile to the Main Nile is found to be $143x10^6$ tons. The paper also reviews the main characteristics of the Blue Nile sediment that affect its transport and deposition.

Keywords: Blue Nile, reservoir sedimentation, Roseires reservoir, Sennar reservoir

INTRODUCTION

The Blue Nile is one of the two main tributaries of the Nile River. It originates from Lake Tana in the Ethiopian Plateau and joins the White Nile at Khartoum. The average annual flow of the Blue Nile is 50 billion cubic meters. Most of this flow occurs during the flood season (July – October). The Blue Nile plays an important role in the economic development of Sudan as more than 90% of the irrigated agriculture and 295 MW of hydropower are produced in the Blue Nile. During its flood season the river brings down considerable amounts of sediment estimated as 146 million tons per year at El Deim. The sediment material originates mainly from heavy erosion in the upper catchment area in Ethiopia. This high sediment load has influenced the design and operation of the reservoirs and the irrigated schemes.

The length of the Blue Nile in Sudan is735 km and its system consists of two reservoirs, Roseires and Sennar, and two tributaries, viz. Dinder and Rahad. Sennar and Roseires reservoirs have lost 65% (DIU, 2010) and 40% (Omer et al, 2014) of their initial storage capacities of 0.93 billion m^3 and 3.024 billion m^3 due to sedimentation, respectively. The Blue Nile sediment in Sudan is monitored by the Ministry of Water Resources at a number of stations scattered along its length. The sediment concentrations vary during the flood season and from a year to another. The sediment load is also variable along the river due to deposition in the river channel, trapping in the reservoirs, diversion to irrigated schemes and inputs from tributaries.

In this paper the Flow-Duration, Sediment-Rating Curve method developed by Miller (1951) is used to estimate the long term sediment entering each reservoir. The sediment trap efficiency of each reservoir is then calculated using the bathymetric survey result. The current trap efficiency of Roseires and Sennar reservoirs are 17% and 5%, respectively. The average annual sediment diverted to Gezira Scheme is 8.5 million tons as calculated from the sediment monitoring records. The paper presents the spatial sediment distribution along the Blue Nile at key river nodes e.g. upstream and downstream each reservoir and at Gezira canals' off takes. The annual average sediment contribution of the Blue Nile to the Main Nile at Khartoum is found to be 153.5 million tons.

The paper also reviews the main characteristics of the Blue Nile sediment that affect its transport and deposition.

SEDIMENT INFLOW TO SUDAN

The Blue Nile brings considerable amounts of sediment during its flood season (July – October). This sediment material originates mainly from heavy erosion in the upper catchments in Ethiopia. The sediment inflow to Sudan is measured at El Deim station in the Ethiopian Sudanese border. The transported sediment in the Blue Nile consists of significant quantities of very fine material composed of silt and clay which can be easily transported in suspension, and under certain hydraulic conditions it is ready to settle fast, (Hussein, 1994). The sediment concentration varies from a year to another and has reached 2.6% by weight at Roseires during the 1988 flood. The sediment concentration also varies throughout the flood season, starting with traces of sediment concentration in mid-June and increases gradually till its maximum concentration in the second period of July and then decreases again and vanishes at the beginning of November. The suspended sediment accounts for approximately 90% of the total sediment load in the Blue Nile. Analysis of sediment data at different sampling stations in the Blue Nile showed a very strong correlation between suspended sediment load and river flow in a loop shape (Hussein, 2006). The sediment rating curve at these stations can be separated into a rising and a falling flood stage curves at the different monitoring stations, Fig (1) shows this phenomenon at Wad ElAis.

Fig (1) shows that the sediment load carried by the same river discharge is higher in the rising limb than in the falling. This is attributed to the fact that at the beginning of the rainy season the catchment has little vegetation cover and the soil is easily eroded but as time passes and grass grows the soil erosion decreases. Another phenomenon that can be attributed to the same fact is the occurrence of the maximum sediment concentration of the Blue Nile three weeks earlier than the peak discharge.

An intensive sediment monitoring program in the Blue Nile and Gezira Scheme was started by the Hydraulics Research Station in 1988. The Blue Nile sediment is monitored at key stations, these stations are: El Deim at the border; Wad El Mahi upstream Roseires dam; downstream Roseires ; Wad ElAis upstream Sennar dam; downstream Sennar dam; and at the off-takes of Gezira and Managil canals at Sennar, (Fig, 2).

Miller (1951) developed a method for estimating the average sediment yield by combining short-term sediment rating curve with long-term flow-duration curve. Using the Flow-Duration, Sediment-Rating Curve method a 44 years flow duration (1966 – 2009) and the sediment rating curves for years (1970, 73, 75, 93, and 1994) at El Deim gauging station, the long term suspended sediment reaching El Deim is estimated at127 million ton, (Table, 1). Adding 15% to cater for bedload sediment transport the total long-term annual sediment inflow is approximately 146 million tons. This figure is in agreement with that of 140 million tons estimated by Hussein et al (2005).

Table (1): Long term mean suspended sediment inflow at El Deim

Month	July			August			September			October		
Period	I	II	III	I	II	III	I	II	III	I	II	III
Qs * (M ton)	7.0	11.1	19.0	21.8	25.7	27.3	4.9	3.7	2.8	1.6	1.0	0.6

*Qs is the suspended sediment load in million tons

SEDIMENT DISTRIBUTION WITHIN SUDAN

Within Sudan there are 11 seasonal streams that flow into the Blue Nile between El Deim and Roseires Dam. These streams bring considerable amounts of sediment load during the rainy season, (Ahmed, 2006). The sediment contribution of these streams is not known. Therefore, the long term sediment inflow to Sudan at EL Deim is considered as the sediment inflow to Roseires dam. Part of this sediment inflow to Roseires is trapped in the reservoir and the remaining part passed downstream to Sennar reservoir. The contribution of the local streams flowing into the river between Roseires and Sennar, and also the abstraction of irrigated schemes in this reach are also not known. Part of the sediment inflow to Sennar is diverted to Gezira Scheme through the main canals. Another proportion is trapped in Sennar reservoir. In its flow to join the White Nile at Khartoum, the released sediment load downstream Sennar dam is joined by the sediment from Dinder and Rahad rivers. The key sediment nodes in the Blue Nile considered in this paper are the sediment inflow to Sudan at El Deim, Wad ElAis, Sennar and Khartoum, (Fig, 5).

SEDIMENTATION IN ROSEIRES RESERVOIR

Roseires reservoir was constructed in 1966 across the Blue Nile some 110 km from the Sudanese Ethiopian border. Roseires has an initial storage capacity of 3.024 billion m^3. The reservoir suffered severe sedimentation and lost 40% of its storage, (Omer et al, 2014). The operation policy adopted for the reservoir is to keep the water level as minimum as possible so as to pass the bulk of the sediment.

The long term annual sediment inflow to Roseires reservoir is estimated as 146 million tons. The trap efficiency of the reservoir is given by:

$$\mathrm{TE}(\%) = \frac{(\mathrm{V_o} - \mathrm{V})\gamma}{TQs} \quad \text{...} \quad (1)$$

Where;
TE = trap efficiency after T years of operation;
V_o = original reservoir volume;
V = volume remaining after T year of operation;
Qs= annual sediment inflow (tons);
γ = average specific weight of deposited sediment over T years (t/m^3).
The specific weight of deposited sediment γ increases with time due to consolidation as fresh sediment gets deposited over the old deposited sediment. γ is calculated using Miller's equation (Miller, 1953) as:

$$\gamma = \gamma_i + 0.434K\left[\frac{T}{T-1}(\ln T)\right] \quad \text{...................................} \quad (2)$$

Where γi the initial value of γ.
Using the same values of γ_i = 1.118t/m^3 and K = 0.0468t/m^3 used by Hussein (2005), the bathymetric survey results for 1976, 1981, 1992 and 1995 the sediment trap efficiency for Roseires reservoir is found to be:

$$TE(\%) = 180.39T^{-0.614}\text{, } R^2=0.99 \quad \text{..............................} \quad (3)$$

Where T=years of operation since 1966. Substituting T=2013-1966=47 for this year 2013 in equation (3) above yields a trapping efficiency of 17%, i.e. about 25 million tons is being deposited in Roseires reservoir in 2013 (before dam heightening).

SEDIMENT TRAPPED IN SENNAR RESERVOIR

Sennar is the oldest dam constructed across the Blue Nile in 1926 some 300 km from the Sudanese Ethiopian border. Sennar reservoir has lost about 65% of its initial capacity of 0.93 billion m^3 due to sedimentation, (DIU, 2010). The reservoir is operated during the flood season similar to Roseires reservoir. The sediment inflow to Sennar reservoir is sampled at

Wad El Ais at the reservoir's mouth, some 70 km upstream. The reservoir's sediment outflow is sampled immediately downstream the dam. The sediment monitoring of Sennar reservoir was started in 1988, (Fig, 3).

Many large seasonal streams flow into the Blue Nile between Roseires and Sennar Dam, e.g. Khor Dunia, which add extra sediment loads to the river during the rainy season, (Ahmed, 2006). On the other hand part of the sediment in the river is diverted to the irrigated schemes upstream Sennar Dam, e.g. Esuki, Abu Naama... etc. The sediment contribution of these seasonal streams is not known, as well as the diverted sediment to the irrigated schemes in this reach is also not known, an exception is the sediment diverted to Gezira Scheme. As for El Deim the Flow-Duration, Sediment-Rating Curve method (Miller, 1951) was used. A 45 years flow duration (1966 – 2010) and 11 years of sediment data (2002-2012) at Wad El Ais gauging station, the long term suspended sediment load entering Sennar reservoir is computed as 159 M ton. This high value may be attributed to the contribution of the streams flowing into the river between El Deim and Roseires which were not taken into account. Also the sediment rating curves for El Deim were obtained from old sediment data. There is an increasing trend in the Blue Nile sediment concentrations and loads (Gismalla 2009). Using reservoir bathymetric survey results of 1986/ 2008/ 2010, the current trap efficiency of Sennar reservoir is estimated as 5%.

SEDIMENT DIVERTED TO GEZIRA SCHEME

Gezira is the largest irrigated scheme in Sudan having an area of 0.88 million hectare. The scheme is irrigated by two main canals, viz. Gezira and Managil canals. The two canals take-off water from Sennar dam and have a total design capacity of 31 million m^3/day. Gezira uses on average about 6.1 Mm^3 of irrigation water annually, (Adam, 2013). Since mid-seventies the scheme faced severe sedimentation problems which lead to the implementation of the famous intensive sediment monitoring program in Gezira Scheme and the Blue Nile in 1988. The sediment entering Gezira scheme has an increasing trend, (Fig, 4). This increasing trend is attributed to the general trend in the Blue Nile sediment concentration and the increased water abstraction due to intensification and diversification of crops in Gezira scheme implemented in mid-seventies.

The annual average sediment diverted to Gezira Scheme at Sennar is calculated in this study as 8.5 million tons.

SEDIMENT INPUT TO THE MAIN NILE

Downstream Sennar dam the Blue Nile receives water from its major tributaries Dinder and Rahad. They rise in the Ethiopian Highlands and join the Blue Nile before its confluence with the White Nile at Khartoum. Both streams are highly seasonal having their flow between July and November. The average annual flow of Dinder and Rahad rivers are about 3.0 and 1.0 billion m^3, respectively, (Ahmed et.al 2008). Dinder River is monitoring at Gawisi and Rahad at Hawata. There is no continuous record of sediment data for the two rivers, but sediment data is available for some seasons for the two stations, (Gismalla, 2004). The average annual sediment load of Dinder and Rahad rivers are 8 and 3 million tons, respectively. Therefore, Dinder and Rahad input additional 11 million tons of sediment annually to the Blue Nile before it confluence with the White Nile. Therefore, the Blue Nile contributes about 153.5 million tons to the Main Nile at Khartoum, annually, (Fig, 5) and (Table, 2). The ongoing Roseires Dam heightening and the construction of the Renaissance dam and other proposed dams in Ethiopia will change the current sediment balance in the Blue Nile.

Table (2): Current sediment distribution along the Blue Nile in Sudan

	River reach / node	Sediment load (M tons)	Comments
1	Contribution of upper Catchment at Deim	146	Long term average, estimated using Miller equation.
2	Contribution of streams Upstream Roseires	Unknown	Ignored in computation
3	Trapped in Roseires reservoir	-25	17% TE
4	Sediment Downstream Roseires	121	
5	Contribution of streams upstream Sennar	Unknown	Ignored in computation
6	Abstraction of irrigation schemes upstream Sennar	Unknown	Ignored in computation
7	Sediment at Wad Elais	159	Long term average, estimated using Miller equation.
8	Trapped in Sennar reservoir	-8	5% TE.
9	Diverted to Gezira Scheme	-8.5	

10	Contribution of Dinder river	8
11	Contribution of Rahad river	3
	Contribution of Blue Nile to the Main Nile at Khartoum	**153.5**

CONCLUSIONS AND RECOMMENDATIONS

- Having two different sediment curves for the rising and falling flood is a catchment characteristic of the Blue Nile.
- The Flow-Duration, Sediment-Rating Curve method developed by Miller (1951) can give reasonable estimates of the long term sediment flows using short term sediment measurements.
- The method is recommended for estimating the sediment contribution of the large streams flowing into the river.
- The overall balance of the sediment shows that, the Blue Nile contributes about 153.5 million tons of sediment to the Main Nile at Khartoum.
- The new developments in the Blue Nile viz. Roseires Dam heightening and the construction of the Renaissance dam in Ethiopia will disturb this sediment balance.
- It is recommended to update incoming sediment load at El Deim using recent sediment data when becomes available.

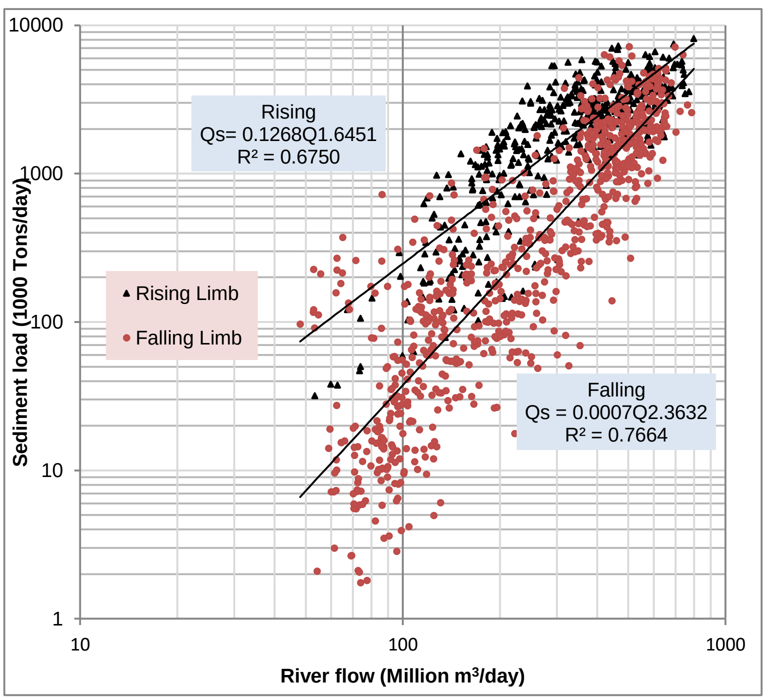

Fig (1): Sediment rating curves for the Blue Nile at Wad ElAis (2002-2012)

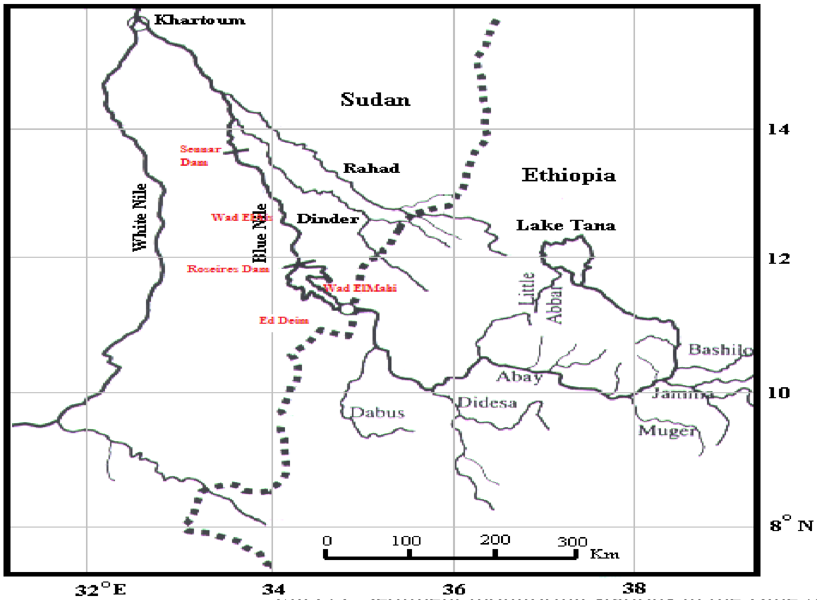

Fig (2): Sediment monitoring stations in the Blue Nile

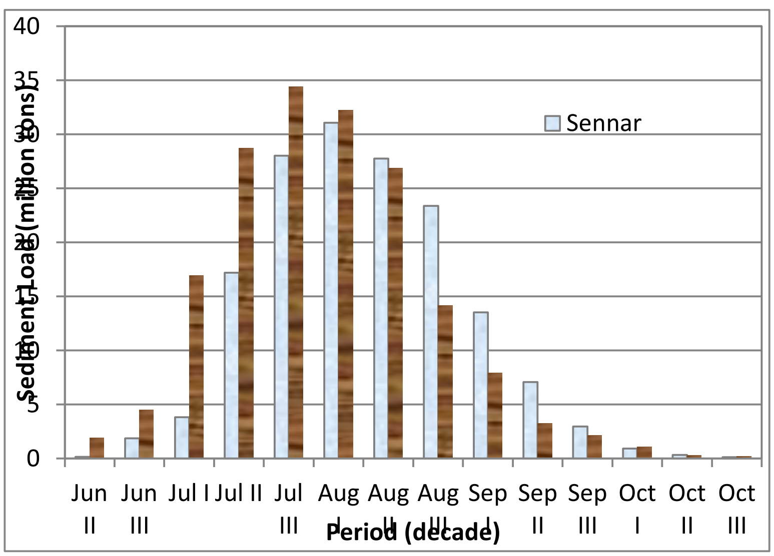

Fig (3): 10-days average sediment load at Wad El Ais and downstream Sennar (2002 -2013).

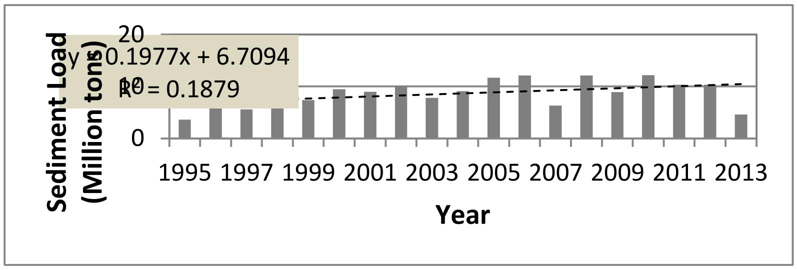

Fig (4): Annual sediment load entering Gezira scheme (Source: Mekawi, 2014)

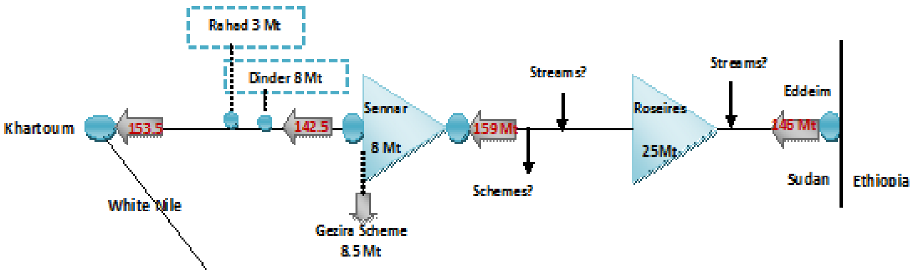

Fig (5): Schematic diagram for the sediment distribution in the Blue Nile

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موزانة الطمي العالق في النيل الأزرق وفروعه في السودان

الملخص

النيل الأزرق هو احد رافدي النيل الرئيسي و مصدره الهضبة الإثيوبية. تلعب مياه النيل الأزرق دورا هاما في التنمية الاقتصادية في السودان من حيث توليد الطاقة المائية وتنمية الزراعية المروية. متوسط الإيراد السنوي للنيل الأزرق هو 50 مليار متر مكعب، 80٪ من هذا الإيراد تحدث خلال موسم الفيضان (يوليو – أكتوبر). ينقل النهر خلال موسم الفيضان كميات كبيرة من الطمي العالق تقدر بـ 146 مليون طن سنويا عند محطة الديم على الحدود السودانية الإثيوبية. المصدر الرئيسي لهذا الطمي هو تعرية صخور المستجمع المائي للنهر في الأحباس العليا في الهضبة الإثيوبية.

يشمل نظام النيل الأزرق في السودان خزانين هما الروصيرص وسنار، واثنين من الروافد وهما الدندر والرهد. فقد خزاني سنار والروصيرص فعلياً 65٪ و 40٪ من قدراتها التخزين الأولية بسبب ترسب الطمي فيهما. تقوم وزارة الموارد المائية برصد الطمي في النيل الأزرق في السودان في عدد من المحطات المنتشرة على طول النهر. يتفاوت تركيز الطمي في النهر خلال موسم الفيضان وكذلك من عام لآخر. تبعاً لذلك تتغير كميات الطمي المنقولة على طول النهر بسبب الترسب في قاع النهر، و التخزين في الخزانات، وتحويل المياه إلى المشاريع المروية وإيرادات روافد النهر.

في هذه الورقة تم حساب كفاءة الترسيب في خزاني الروصيرص و سنار باستخدام البيانات المتاحة من المسح المائي. حيث وجد أن كفاءة الترسيب الحالية لخزاني الروصيرص وسنار هي 17٪ و 5٪ على التوالي. بينما متوسط الطمي الداخل لمشروع الجزيرة هو 8.5 مليون طن سنوياً. كذلك تم حساب توزيع الطمي على طول النيل الأزرق من الحدود الإثيوبية وحتى نقطة إلتقائه بالنيل الأبيض في عدد من المحطات الرئيسية. هذه المحطات تمثل مداخل و مخارج الخزانات، مآخذ ترعتي الجزيرة و المناقل في سنار وعند نقطة إلتقائه بالنيل الأبيض في الخرطوم. أوضحت هذه الدراسة أن مساهمة النيل الأزرق من الإطماء في النيل الرئيسي عند الخرطوم هو 153.5 مليون طن. كما تعرضت الورقة للخصائص الرئيسية للطمي في النيل الأزرق والتي تؤثر على النقل والترسيب.