Water Balance Assessment of the Roseires Reservoir

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Abstract

Roseires Reservoir on the Blue Nile River was completed in 1966 to serve the purposes of hydropower generation, irrigation and flood retention. During its lifetime, the reservoir suffered from serious sedimentation, to the limit that its present capacity is less than 2 cubic kilometers (km^3). Operation of the reservoir is maintained closely together with the Sennar Dam according to the operation policy. Operation of reservoirs depends on rules set for that purpose, which is based mainly on the water balance of the system among other factors. Such rules are rarely revised during the lifetime of the reservoirs. Roseires is not an exception. This paper presents an attempt to look closely at the different aspects of the operation and water balance parameters to gain an insight into the whole operation of the reservoir. In addition, an attempt is also made to find an accurate balance formula for the system, taking into account the part of the intervening catchment (14,578 km^2) that is totally ungauged. The flow from the Ethiopian Highlands is monitored at Eddeim Station. The mean annual rainfall in the area amounts to approximately 700 mm. The daily evaporation rates were derived from monthly data available in the operation rules of the Blue Nile reservoirs. The change in reservoir storage (Δs), and surface area were computed from the bathymetric surveys conducted during 1985, 1992 and 2005. Water balance computations were carried out for 1985, 1995 and 2005, corresponding to the availability of data. The ten years bathymetric data survey intervals give enough time for changes in water balance to take place, if any. Daily and 10-day water balances were computed using Eddeim flow data as the only inflow to the reservoir for the whole year, and for the dry and rainy periods. It was found that outflow from the reservoir can be reproduced with an efficiency of 97% R^2, indicating that the contribution of the intervening catchment to the inflows is negligible.

Introduction

The Nile River, which is shared between (10) countries, is the primary source of Sudan water. The Blue Nile sub system in this respect accounts for 76% of the total irrigated agriculture on the three Nile tributaries (Atbara, White Nile and Blue Nile). A major characteristic of the Blue Nile discharges is the remarkable seasonality of its flow. More than 80% of the river discharge flows during the flood months, (June – October). Two Dams were built across the river (Sennar, 1925 and Roseires, 1966) to partially control the flows. The two dams serve about 2.7 million feddan of the Sudan irrigated area, as well as more than 40% of the total hydropower generation of the country.

The Roseires dam, which spans the Blue Nile 630 km upstream of Khartoum, is a 1000 m long and 68 m high concrete dam with the crest at 482.2 m. The dam was completed in 1966 to be used for irrigation water supply and hydropower. The dam contains 5 deep sluices and a

gated spillway, consisting of 7 units, with a maximum discharge capacity at level 480 m of 16500 m3/s. The hydro-electrical potential amounts to 212 MW.
The volume of the reservoir was originally 3.0 milliard m3 at a level of 480 m with a surface area of 290 Km2 extending over a length of 75 Km. The storage capacity has considerably been affected by siltation and is now about 30 percent less. The recent capacity is estimated to be about 2.1 milliard m3. A special operation strategy, maintaining low reservoir level and high flow velocities during the passage of the flood, is applied to reduce the siltation.
The main inflow to the reservoir is monitored at eddeim station 102 km south-east of Roseires dam on the Ethiopian/Sudanese border. This allows for an intervening catchment of 14,578 Km2 which is totally ungauged. As well the rainfall over the reservoir lake is monitored at Damazin stations. The significance of the contribution of the intervening catchment and the direct rainfall over the reservoir is alleged to be negligible.
Operation of reservoirs depends on rules set for that purpose, which is mainly based on water balance of the system among other factors. Such rules are rarely revised during the life time of the reservoirs and Roseires is not an exception.
This study is an attempt to closely look at the different aspects of the operation and water balance parameters to have an inside about the whole operation of the reservoir. In addition, to attempt finding accurate balance formula for the system, bearing in mind the part of the intervening catchments and the direct rainfall over the reservoir.

The Study area

Roseires Dam was completed in 1966 with an initial capacity of 3.024 Km3 at level 480 m level. The main objective to supply irrigation demands as first priority, and hydropower generation comes secondly. During its lifetime, the reservoir suffered from serious sedimentation to the limit that, its present capacity is less than 2.0 Km3.Operation of the dam is maintained closely with Sennar dam, according to the operating policy. Discharge in Roseires dam through gates (deep sluices and spillways) is computed by the dam operation engineer using flow charts prepared from a physical model before dam construction in 1965.

The deep sluices with sill levels of 435.5m amsl are used to pass the main volume of the flood, and to flush the sediment as much as possible. The deep sluices are always closed in low flow seasons to reduce the possibility of cavitations damage on the downstream apron at low tail water levels. The spillways with sills at 463.7m amsl are used to pass the peak of major floods and also, if necessary, to augment the downstream flows in the low flow season to provide the releases required for irrigation and other down stream water utilizations. At the extremities of the concrete section on each bank provision has been made for gravity supplies for future irrigation canals. On the west bank the head works would supply a future scheme in the Kenana area and on the east bank; supplies could be made for a future irrigation scheme in the Rahad, Dinder or Rosaries areas.

When the existing Rosaries dam was constructed provision was made for the future construction of a power station with seven generating units. In 1971 three units, each with a name plate rating of 30 MW were installed. The other four units were installed and commissioned later in January 1979. These sets have turbines similar in size to those of the first three units, but the generator name plate rating has been increased to 40 MW.
According to the design, the maximum retention level of the reservoir is 480.0m amsl.; however a study in 1973 (Sir Alexander Gibb & Partners, 1973.) came to the conclusion that the reservoir could probably be filled to 481m each year for a limited number of years without

incurring an unacceptable degree of risk. Nevertheless the operating range of the reservoir is kept between 467m and 480m.The live storage volume between these two levels is about 2386 million m^3, which is released for use downstream between November and June. The reservoir is held at the lower level through the flood season to minimize sediment deposition and is filled to 480m on the falling flood when the sediment load is much lower. A recent bathymetric survey has indicated that since the dam was built some 1.408 milliard $m^3$of the sediment has been deposited in the reservoir (HRS 2006), this definitely will affect the storage characteristics of the reservoir.

The design of the present dam made provision for a subsequent increase in height of ten meters. The limitation on the extent of the heightening was dictated by the necessity to avoid creating adverse effects in Ethiopia. The foundations and first few meters of buttress deepening required for the ultimate height were provided for in the initial construction and the sections of the concrete dam adjoining the earth dam were built to the ultimate profile. Dam heightening will be accompanied with extension in earth embankment bringing the total length of the dam to about 25km. Figure (1) shows the location of the reservoir together with the eddeim station. Figure (2) shows the longitudinal profile along the Blue Nile.

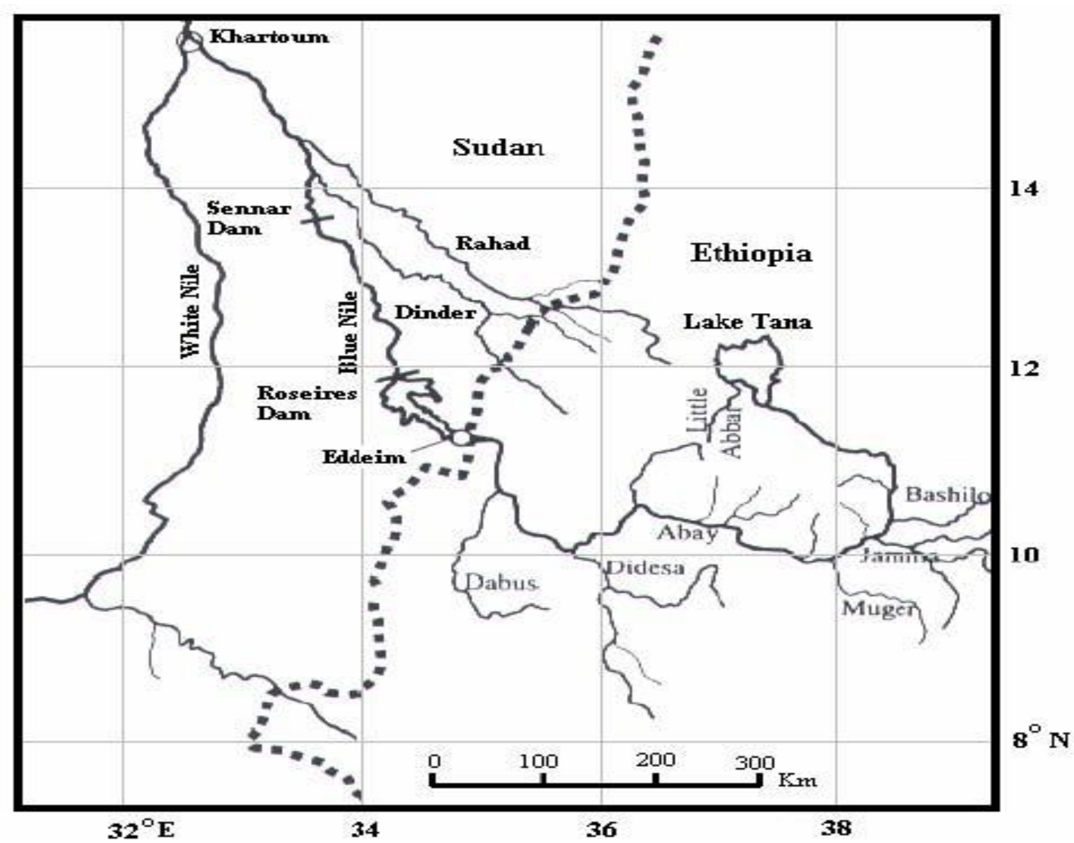

Figure 1: The Location of Roseires Dam and the Eddeim station within the Blue Nile in Ethiopia and Sudan

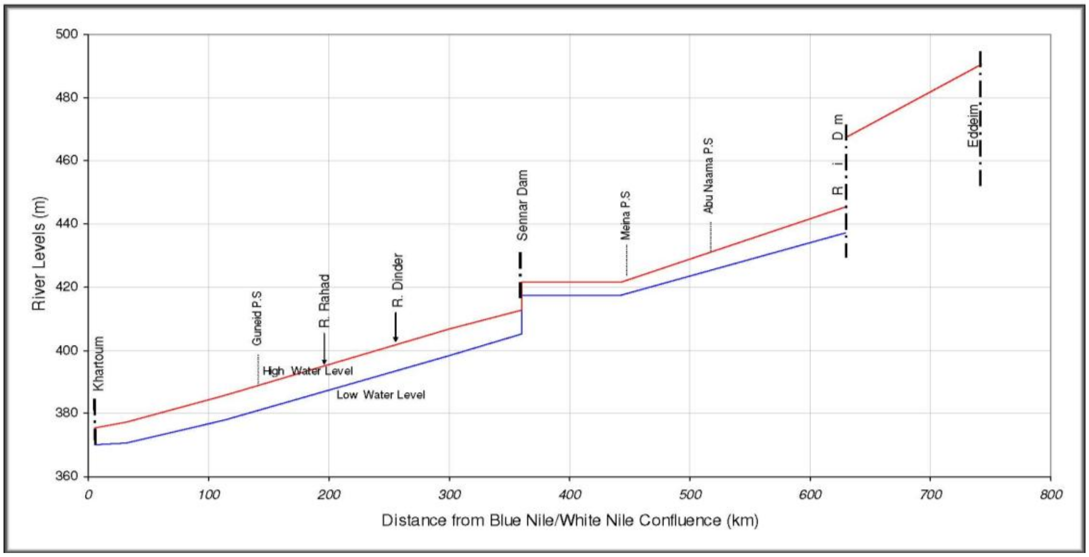

Figure 2: Longitudinal Profile of the Blue Nile

The data

The data required for this study comprises flow data at eddeim, the dam releases, rainfall data, evaporation data, reservoir characteristics and operation rules. These data is collected from the Nile Waters Directorate (NWD) of the MoIWR and Hydrological Year Books published by NWD.

The historical records of daily flows and water levels at Ed Deim and Roseires measuring stations were available from 1965 to 2007. Table (1) shows the availability of the collected data.

Table 1 The gauging sites under study

Gauging Site	Date of Erection	Latitude X°Y´N	Longitude X°Ý E	Gauge Zero (m)	Data Type	Period Covered
Eddeim	1966	11 14	34 59	481.2	H, Q	1966-2007
U/S Roseires	1966	-	-	3.0	H	1966-2007
D/S Roseires	1966	11 50	34 23	3.0	H, Q	1966-2007

Evaporation data is available from Table (2) of the Blue Nile Waters Study, Volume 3. In this table the annual average Penman-evaporation is given in mm/day for the hydrological years 1962/63 to 1972/73. The project area was divided in five climatic zones of which the Roseires dam lies in the Southern Zone. The average annual evaporation for this Zone varies from 5.7 to 6.3 in the considered period.

More recent climate data including values up to 1990 are available from database of CROPWAT of the Food and Agriculture Organization of the United Nations (FAO). Climate data is taken from the Damazin station which is located close to the Roseires dam. This data base provides long term average values for e.g. rainfall and evapotranspiration for each month. From this data base the monthly distribution of annual evapotranspiration can be obtained.

For consideration of the evaporation from the reservoir the evapotranspiration needs to be reduced to the evaporation by application of the formula ET0 = Kp * E0. The factor Kp can be obtained from Table 5 of the FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration.

Table 2 Reservoir evaporation values of Roseires reservoir

Month	Mean daily evapo-transpiration	Kp	Mean monthly evaporation *)	Mean monthly evaporation	Mean monthly rainfall	Mean monthly net evaporation	Percent
	mm/day		mm/day	mm/month	mm/month	mm/month	%
January	5.43	0.70	6.98	216.4	0.0	216.4	12.9
February	6.04	0.70	7.77	217.4	0.0	217.4	13.0
March	6.67	0.70	8.58	265.8	1.0	264.8	15.8
April	6.89	0.70	8.86	265.8	19.0	246.8	14.7
May	6.70	0.70	8.61	267.0	40.0	227.0	13.5
June	5.75	0.75	6.90	207.0	119.0	88.0	5.2
July	4.37	0.85	4.63	143.4	181.0	-37.6	-2.2
August	4.09	0.85	4.33	134.2	203.0	-68.8	-4.1
September	4.48	0.85	4.74	142.3	129.0	13.3	0.8
October	4.85	0.80	5.46	169.1	41.0	128.1	7.6
November	5.09	0.80	5.73	171.8	3.0	168.8	10.1
December	5.34	0.70	6.87	212.8	0.0	212.8	12.7
Total/Average	5.48		6.62	2,413.3		1,677.3	100.0

*) attanuation factor of 0.9 to adjust values to those of the southern zone in table 2.5 of the Blue Nile Waters Study

Methods

Water balance computation was done for years 1985, 1995 & 2005. The selection of these years was due to the facts that during these years bathymetric surveys were done in the reservoir. It can be seen from the selection that the interval is ten years which gives good time for changes in water balance to take place and a period of 20 years can be covered.

During the period January to May, the gates are completely closed and water passes through power turbines only. The discharge through the turbines was used to be monitored by gauges, erected on the penstock of the turbines. However, since 1980's, those gauges were out of order and the discharge was then computed indirectly from the amount of generated energy.

The calculations of the inflow-outflow water balance were carried out to illustrate the relationship between the annual flows of the upstream and downstream measuring stations within each system, taking into account the inter-flows, local abstractions and other related factors.

This has clearly showed the deviations that might have occurred throughout these systems over the years.

The water balance equation of the Blue Nile at Roseires Reservoir can be written as:

$$QEd + Runoff = QRos + losses + \Delta s$$

Where

QEd = Discharge from Ed Deim

QRos = Release from Roseires

Runoff = Runoff from catchment between Ed Deim and Roseires

Losses = evaporation and seepage losses if any

Δs = change of storage content of Roseires reservoir

Results and Discussion

The application of water balance on daily basis was performed. The results for the three years namely (1985, 1995 and 2005) are given respectively in figure (3) to figure (5).

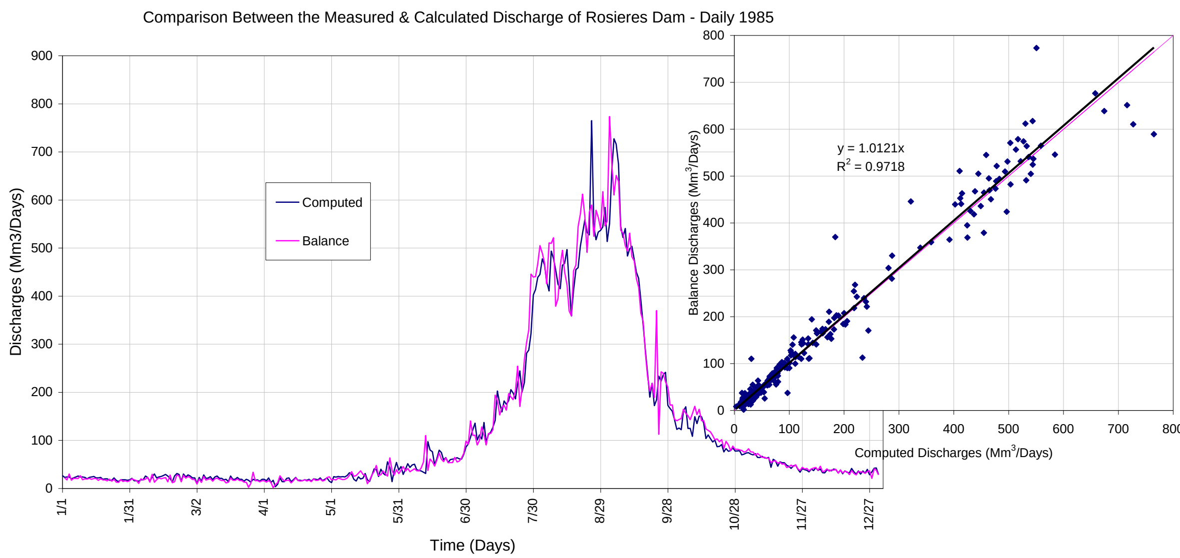

Figure 3: Comparison between the Computed & Balance Calculated Discharge of Rosieres Dam - Daily 1985

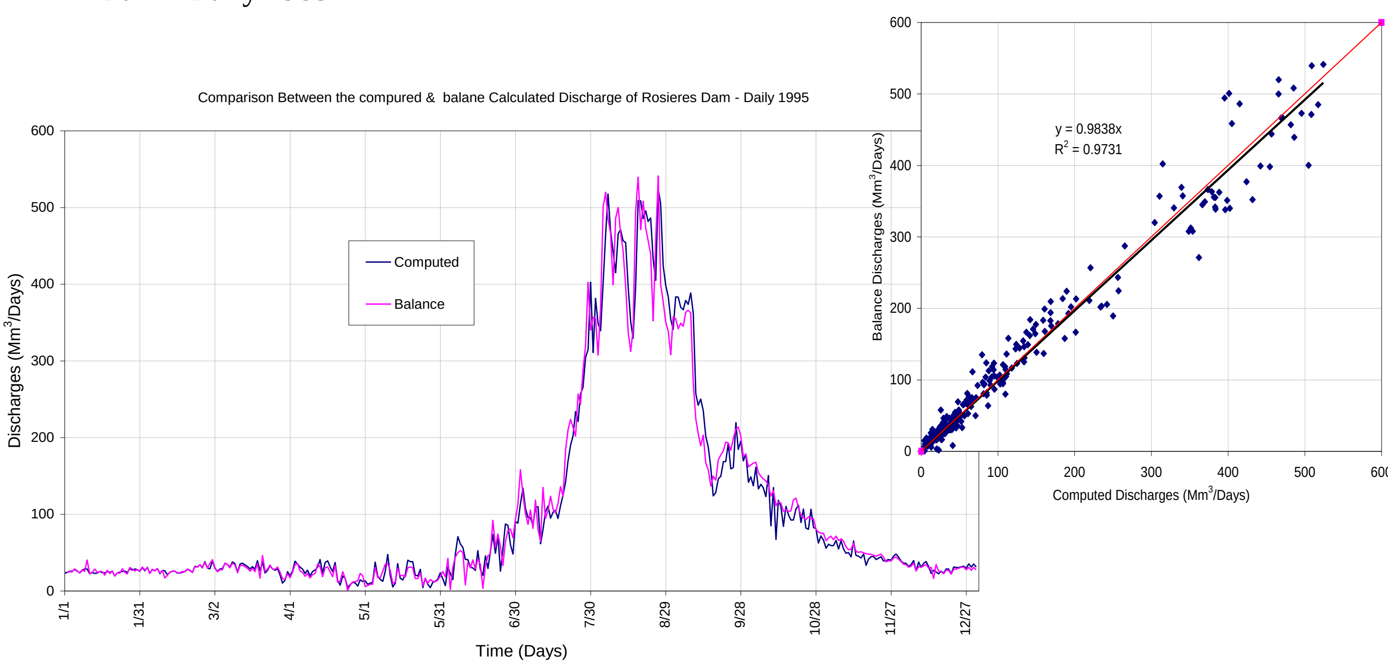

Figure 4: Comparison between the Computed & Balance Calculated Discharge of Rosieres Dam – Daily 1995

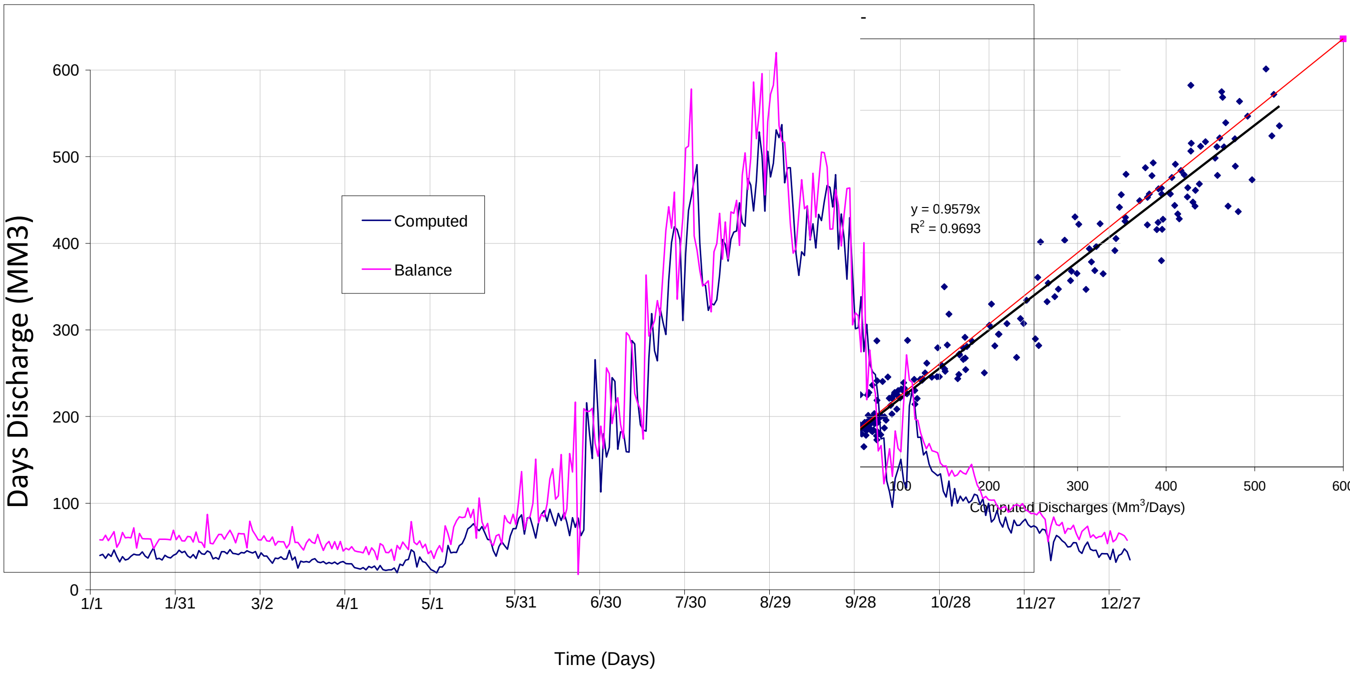

Figure 5: Comparison between the Computed & Balance Calculated Discharge of Roseires Dam - Daily 2005

The over all performance of the water balance on daily basis is relatively high which accounts for 97% of the initial variance. It should be noted that the calculation of water balance does not take into consideration the contributions of the intervening catchment and direct rainfall over the reservoir. This indicates that these contributions are insignificant.

10-Days water balance at Ed Deim Station (Back Routing):

The water balance is performed at 10 days time step at Ed Deim station.

Ed Deim station was chosen because of its stable river section (deep gorge) at the site. Although discharge measurements using cable at Ed Deim was ceased since1972, the recorded flow by staff gauge is believed to be reliable up to date.

As the balance of the river and the reservoir is greatly affect by season, in this work two periods were considered. These are:

- Flood period from 1st June to 31 November (with rain fall),
- Dry period from 1st December to 31 May (without rain fall).

Dry Period (December – May):

During the low flow period, December to May, usually, the dam gates are completely closed and flow is entirely through the power turbines. Leakage through spillways and deep sluices is negligible, which means validation of dam releases during low flow period, is actually validation of the discharge through power station. The discharge through the turbines is computed from the power equation P=γQH, knowing the power P, head H and efficiency γ, the discharge Q is calculated.

The water balance results for years 1985, 1995 and 2005 were obtained for the dry season of ten days interval and compared with the observed discharge at Ed Deim. The results are shown in figure (6) to figure (8).

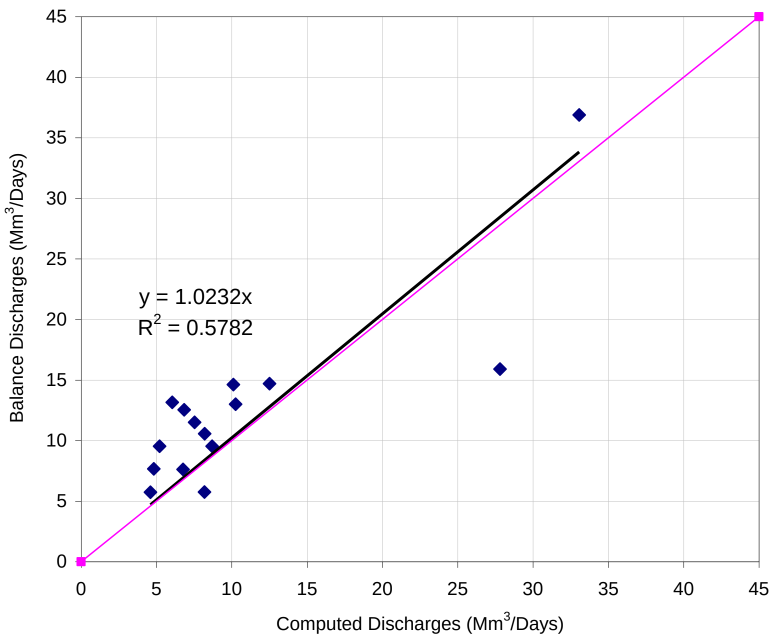

Figure 6: Relationships between the Computed and Observed Discharge at Ed Deim Station - Dry (Jan-May 1985)

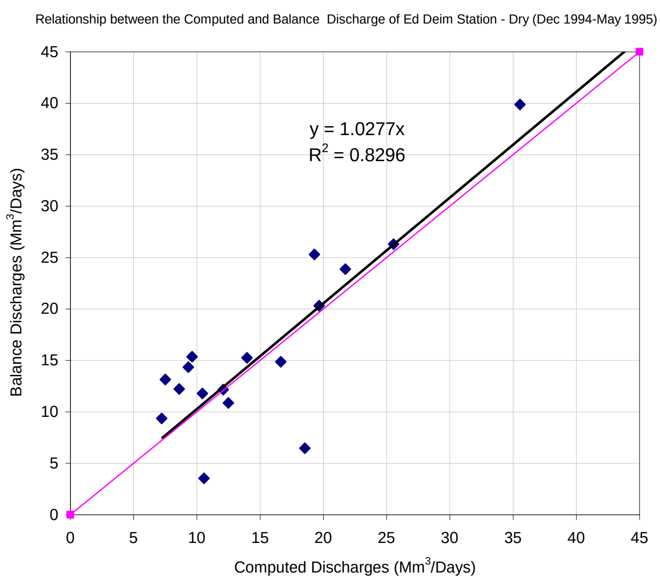

Figure 7: Relationship between the Computed and Observed Discharge at Ed Deim Station - Dry (Dec 1994-May 1995)

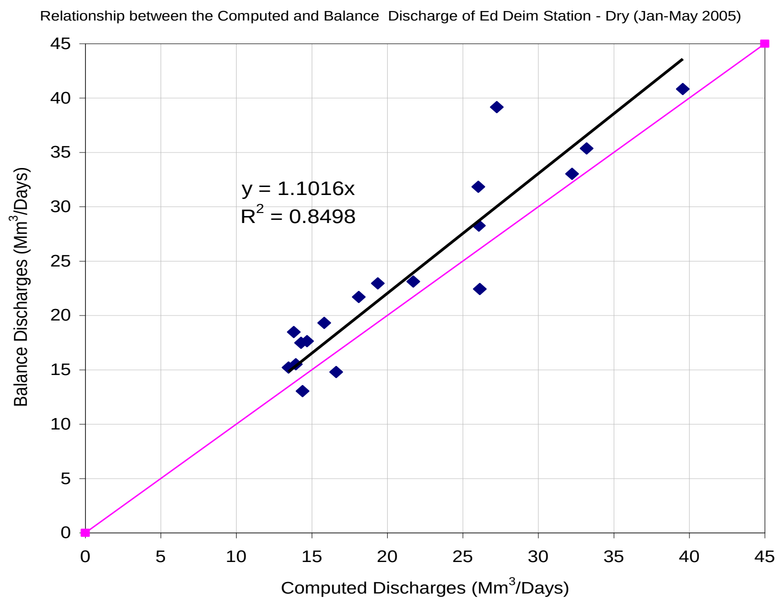

Figure 8: Relationships between the Computed and Balance Discharge at Ed Deim Station - Dry (Dec 2004-May 2005)

Flood Period (June – November):

The water balance for the wet season was also done for Ed Diem station. The results are shown in figure 9 to figure 11 respectively for the three years 1985, 1995 and 2005.

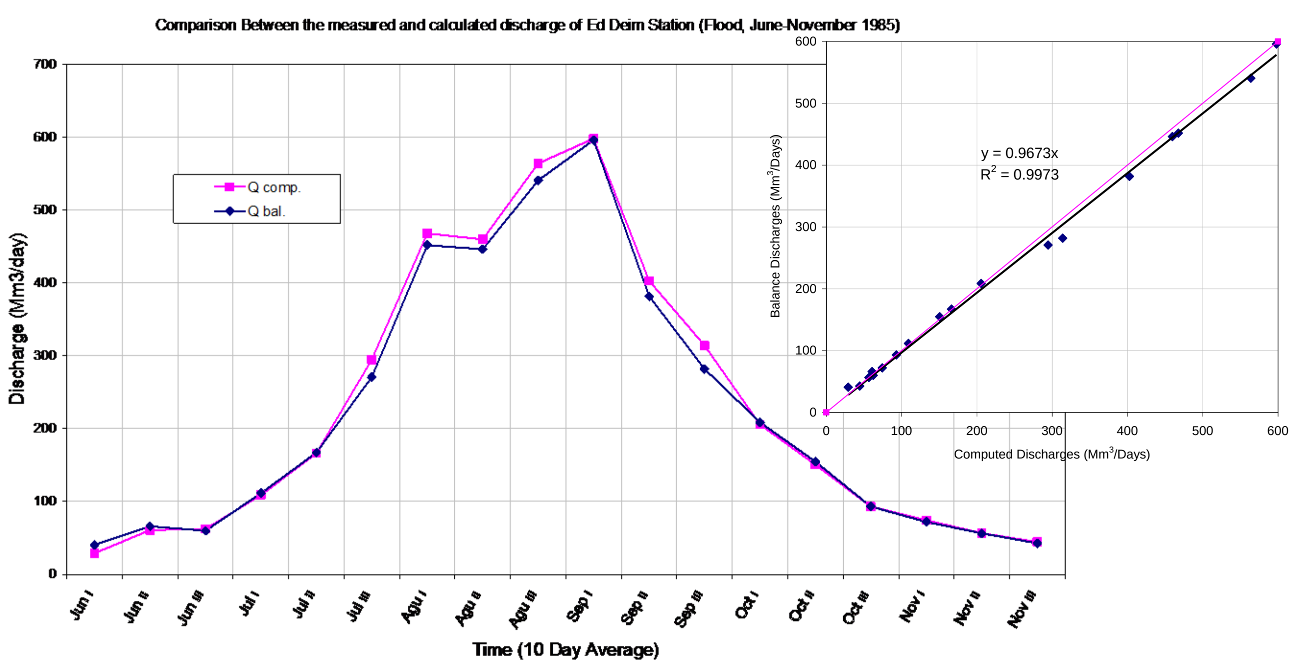

Figure 9: Comparisons between the Computed & Balance Calculated Discharge at Ed Deim Station - Flood (June-November 1985)

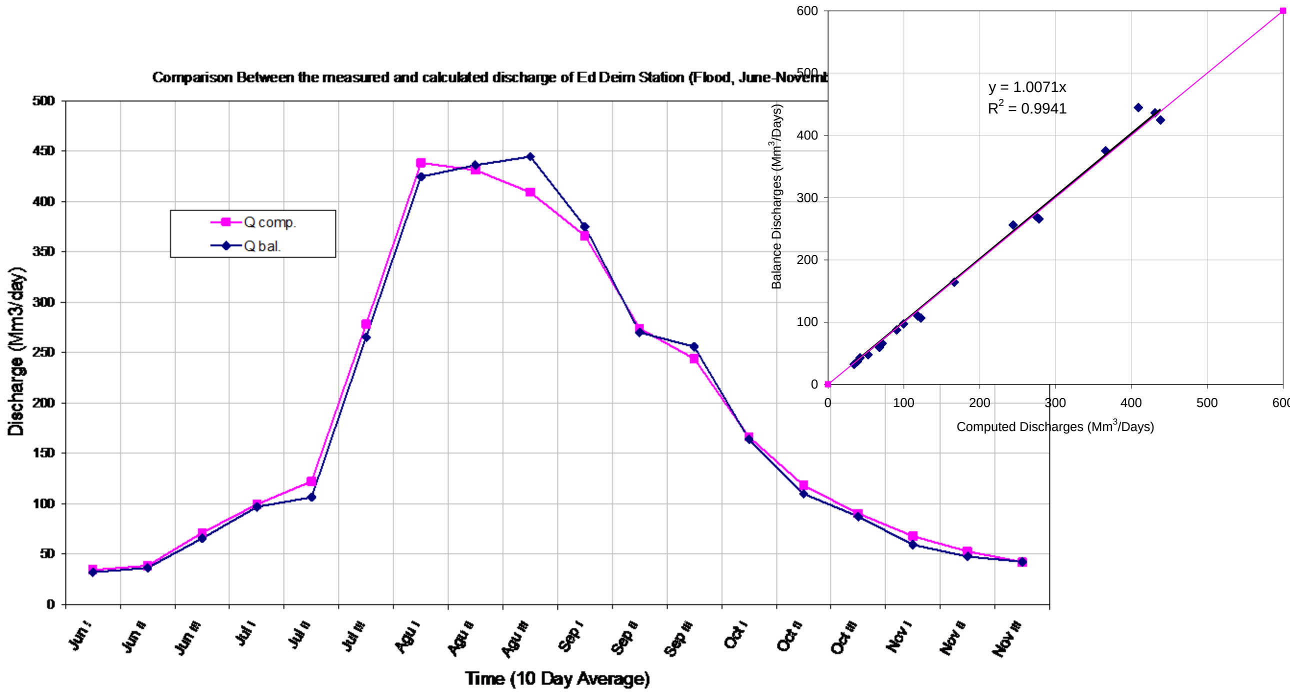

Figure 10: Comparisons between the Computed & Balance Calculated Discharge at Ed Deim Station - Flood (June-November 1995**)**

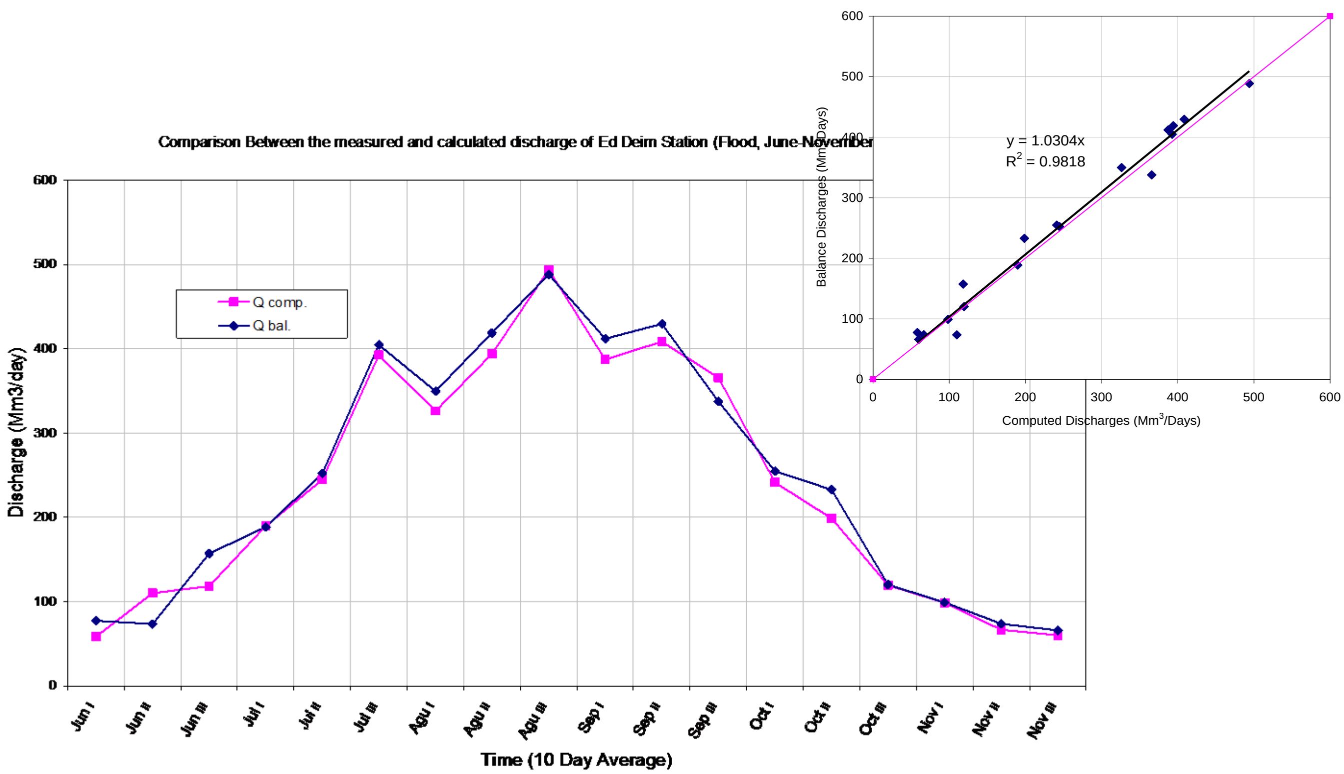

Figure 11: Comparison between the Computed & Balance Calculated Discharge at Ed Deim Station - Flood (June-November 2005)

Daily water balance at Ed Deim – Dry Period (December – May):
The water balance for daily basis for the dry season in Ed Diem was performed the results are shown in figure 12 to figure 14.

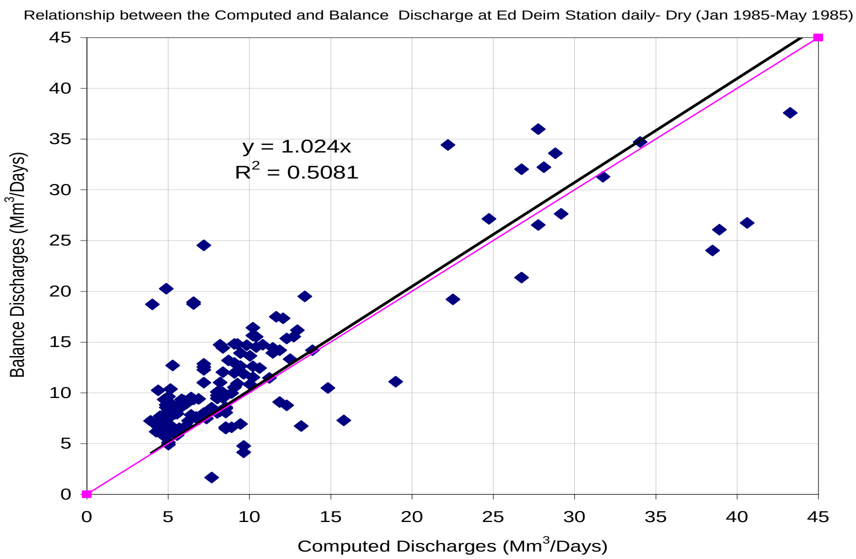

Figure 12: Comparison between the Computed & Balance Calculated daily Discharge at Ed Diem –Dry (Jan 1985 – May 1985)

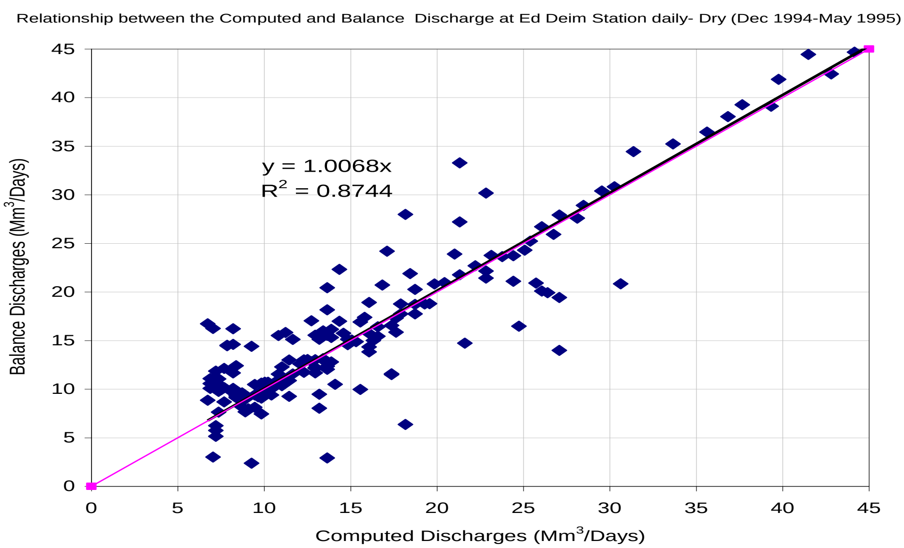

Figure 13: Comparison between the Computed & Balance Calculated daily Discharge at Ed Diem –Dry (Dec 1994 – May 1995)

It is observed that the balance discharge for 1985 is always higher than the computed discharge. The error in the water balance in this period is not systematic compared with water level downstream Roseires dam. These errors in the balance calculated discharge occurred due to the storage as shown in figure 12. It is observed that the result of the balance in 1995 is almost symmetric expect for the period after 20 April as shown in figure 13

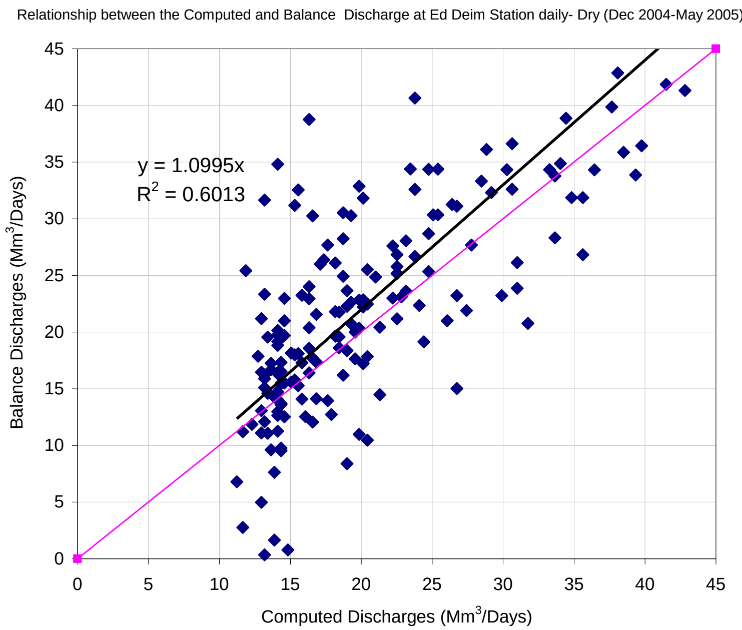

Figure 14: Comparison between the Computed & Balance Calculated daily Discharge at Ed Diem –Dry (Dec 2004 – May 2005)

The result of the balance in 2005 is not good at all and this may be due to the quality of data (the bathymetric survey of 2005 is not accurate).

Conclusion and Recommendations

References