Optimal Operation of the Blue Nile System in Sudan before and after the Grand Ethiopian Renaissance Dam

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ABSTRACT

The Ethiopian Government began constructing The Grand Ethiopian Renaissance Dam (GERD). This dam is expected to affect Sudan which is dependent on the Blue Nile. In this situation there is a clear need to assess these downstream impacts.

Against this background, a simulation and optimization model for a multi-purpose cascade of reservoirs has been developed to provide an optimal operation of the Blue Nile System in Sudan for both current and future situation (before and after GERD becomes operational) under three scenarios (dry, average and wet years). Two objectives were considered in the development of this optimal operation: maximizing hydropower generation and maximizing the new irrigation area that becomes potentially available after the heightening of Roseires. The model was called the Excel-based Blue Nile Simulation and Optimization Model or EBSOM.

The results of EBSOM before GERD becomes operational showed that the maximum area that could be planted was 525,000 hectares. This area will decrease the annual energy production of Roseires reservoir by 9.1% at minimum and 23.5% at maximum.

The results showed that if the filling and operation of GERD is carried out in consultation with Sudan and Egypt, it can be expected that there will be several benefits especially in terms of irrigation and hydropower generation. However, there are also some negative consequences that need to be further studied and addressed.

Keywords: *Multi-Objective Optimization, Non-Linear Programming, Genetic Algorithms, Excel-based model, Simulation of multiple reservoir system, Hybrid Simulation-based Optimization, GERD, Roseires heightened dam, Blue Nile, Sudan, Ethiopia*

بدأت الحكومة الإثيوبية بناء سد النهضة الإثيوبي (GERD) . من المتوقع أن يؤثر هذا السد على السودان المعتمد على النيل الأزرق. في هذه الحالة ، هناك حاجة واضحة لتقييم هذه الآثار الجانبية.

على هذه الخلفية ، تم تطوير نموذج لسلسلة من الخزانات متعددة الأغراض لتوفير التشغيل الأمثل لنظام النيل الأزرق في السودان للوضع الحالي والمستقبلي (قبل وبعد بدء تشغيل GERD) في إطار ثلاثة سيناريوهات :سنوات جافة ، متوسطة ، وسنوات رطبة. تم النظر في هدفين في تطوير هذه العملية المثلى: زيادة توليد الطاقة الكهرومائية وزيادة مساحة الزراعة والري الجديدة التي قد تصبح متاحة بعد تعلية خزان الروصيرص .وقد أطلق على هذا النموذج EBSOM.

أظهرت نتائج EBSOM قبل بدء تشغيل GERD أن المساحة القصوى التي يمكن ريها هي 525000 هكتار .هذه المساحة ستقلل إنتاج الطاقة السنوي لخزان الروصيرص بنسبة 9.1٪ كحد أدنى و 23.5٪ كحد أقصى.

أوضحت النتائج أنه إذا تم تنفيذ وتشغيل سد النهضة بالتشاور مع السودان ومصر ، فإنه من المتوقع أن تكون هناك فوائد عديدة خاصة فيما يتعلق بالري وتوليد الطاقة المائية .ومع ذلك ، هناك بعض النتائج السلبية التي تحتاج إلى مزيد من الدراسة والمعالجة.

كلمات البحث :نموذج متعدد الأهداف ، البرمجة اللاخطية، الخوارزميات الجينية، نموذج يستند على إكسل، محاكاة نظام خزانات متعددة ، سد النهضة الأثيوبي ، تعلية الروصيرص، النيل الأزرق ، السودان ، إثيوبيا

1 Introduction

The Ethiopian Government began constructing a huge hydroelectric dam on the Blue Nile (Abbay) in 2011 and named it the Grand Ethiopian Renaissance Dam (GERD) [1]. This dam is expected to affect the downstream countries (Sudan and Egypt) which are mostly dependent on the Blue Nile. These effects need to be assessed and dealt with, especially during the first years when GERD is filled and during its operation after that.

As the Blue Nile constitutes about 58% of the average annual flow of the River Nile, it represents the major source that the schemes depend on. During the recession period, the percentage of the annual average inflow of the Blue Nile is only about 28%. In 2006 the Government of Sudan decided to implement the project of raising Roseires dam [2].

1.1 Problem Identification

Sudan finished heightening of Roseires Dam by ten meters towards the end of 2012. This increased its live storage from around 2 Km^3 to around 6 Km^3 [2]. The extra storage prompted several extensions of existing irrigation projects and implementation of newly proposed irrigation projects. The maximum area that could be planted in these proposed irrigation projects is still to be determined.

Additionally, the lack of enough capacity of dams combined with the small river flows and the high irrigation demands escalated conflicts between farmers and the Ministry of Irrigation and the Power Authority. This resulted in a conflict of two water functions (irrigation and hydropower). Therefore an optimal management of the Blue Nile water is vitally needed in order to meet the demands of both hydropower and irrigation before GERD becomes operational.

After GERD becomes operational, it will have effects on the Blue Nile System performance in Sudan. These effects need to be assessed and dealt with. In other words, the Blue Nile System operation requires revision after GERD becomes operational.

To conclude, the aim of this paper is to get the optimal operation of the Blue Nile system in Sudan before and after the GERD becomes operational.

1.2 Objectives and Scope of the Study

The main objective of this study is developing a framework of integrated water resources optimization modelling for the Blue Nile System in Sudan.
This main objective can be addressed via a number of more specific objectives which are:

1. Maximizing the benefits from the extra storage of Roseires Dam for the different uses in Sudan before GERD becomes operational.
2. Identifying the maximum possible area to be planted in the newly proposed Rahad II irrigation project.
3. Quantifying and simulating the hydrological effect of GERD after it becomes operational on the Blue Nile system in Sudan.
4. Optimizing the operation of the multiple reservoir system (GERD, Roseires and Sennar) as one system to meet the downstream requirements and optimize the irrigation and hydropower generation for the benefit of all.

2 Approach and Methodology

2.1 Developing EBSOM

A simulation and optimization model for multi-purpose cascade of reservoirs has been built as part of this research to provide an optimal operation of the Blue Nile System in Sudan for both current situation (before GERD becomes operational) and the future situation (after GERD becomes operational) under three scenarios (dry, average and wet years). The model was therefore named the Excel-based Blue Nile Simulation and Optimization Model or EBSOM.

EBSOM has been implemented based on the mass-balance equation, i.e. the mass that enters a system must, by conservation of mass, either leave the system or accumulate within the system. It uses a simulation period of one hydrological year - which starts on the first of July and ends on the 30th of June - with a time step of 10-days.

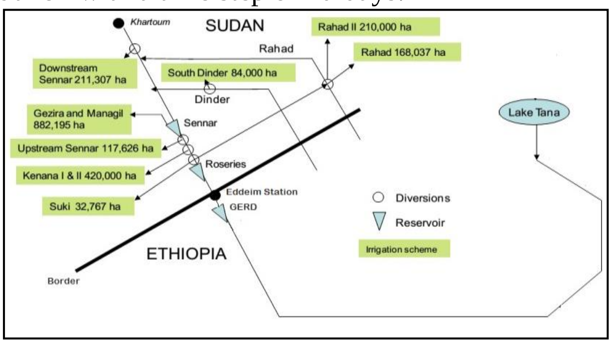

Figure (1): Schematization of the Blue Nile System

The input of EBSOM has been the natural flow of Eddeim Station - located 100 Km upstream Roseires reservoir - for three scenarios, a dry year (80% probability of exceedance), an average year (50% probability of exceedance) and a wet year (20% probability of exceedance). The 80% year flow is the average annual flow of a year that is expected to be exceeded in 80 years out of 100 years. The main output of EBSOM is the annual energy production of Roseires reservoir. EBSOM can also provide additional outputs which are: the level of satisfaction of irrigation demands and the maximum areas that can be planted in Rahad II irrigation project or any extension on existing projects.

During the flood period (July-August) due to high sediment load, Roseires reservoir is kept at its minimum operation level (MOL) of 469.00 m and Sennar is kept at 417.20 m to flush most of the sediment. Then filling of Roseires may start by using one of the two developed criteria (which will be explained in 4.3), which will fill the reservoir to its full supply level (FSL) in October. This means that the filling criteria and the operation of Roseires reservoir for the first four months (July, August, September and October) will be constant.
By using Rahad II as a case generator, EBSOM was run for six cases:

i) Before Rahad II irrigation scheme is implemented (Area = zero)
ii) When the area is 50% of the suggested area of Rahad II (Area = 105,000 hectares).
iii) When the area is 100% of the suggested area of Rahad II (Area = 210,000 hectares).
iv) When the area is 150% of the suggested area of Rahad II (Area = 315,000 hectares).
v) When the area is 200% of the suggested area of Rahad II (Area = 420,000 hectares).
vi) When the area is 250% of the suggested area of Rahad II (Area = 525,000 hectares).

These six cases have been applied for three scenarios, which are a dry year, an average year and a wet year. In each case, the downstream releases of Roseires reservoir for every 10-day period starting from the first period of November until the third period of June (24 10-daily time steps) should be optimized in order to get the maximum total annual energy production of Roseires reservoir.
Two optimization techniques were used to get the optimal releases of Roseires reservoir that gives the maximum total annual energy production. EBSOM was combined with both Non-Linear Programming algorithm (Generalized Reduced Gradient (GRG2) Algorithm) via Microsoft Excel Solver and Genetic Algorithms via GANetXL.

In phase (2), after the operation of GERD, the filling criteria were not applicable anymore and EBSOM was run for a simulation period of one hydrological year - from the first period of July until the last period of June - which was presented in 36 10-day period time steps.

Figure (2) shows a detailed flowchart describing the logic flow for the simulation part of EBSOM.

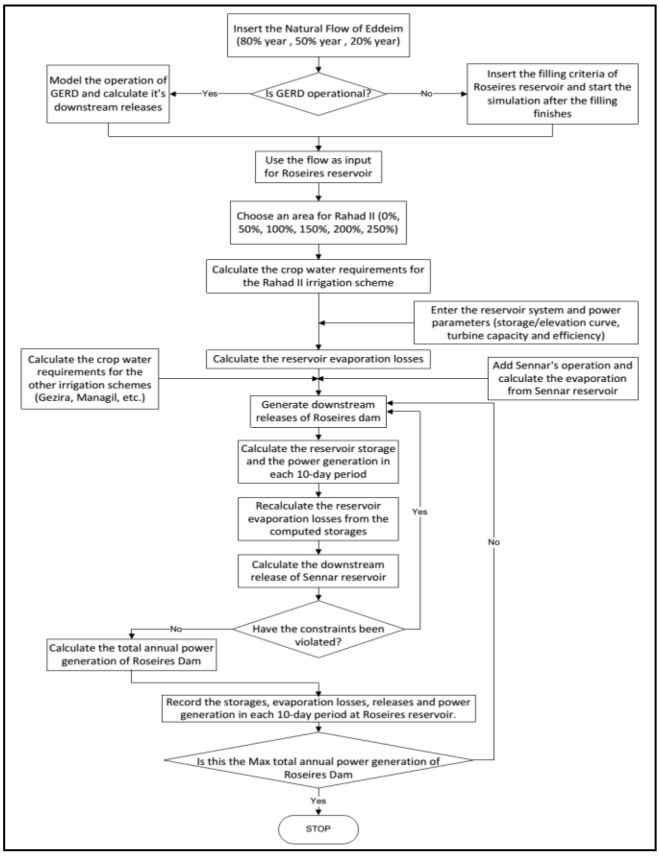

Figure (2): Flowchart of EBSOM

Figure)3) shows the coupling of the optimization tools with the simulation model of EBSOM

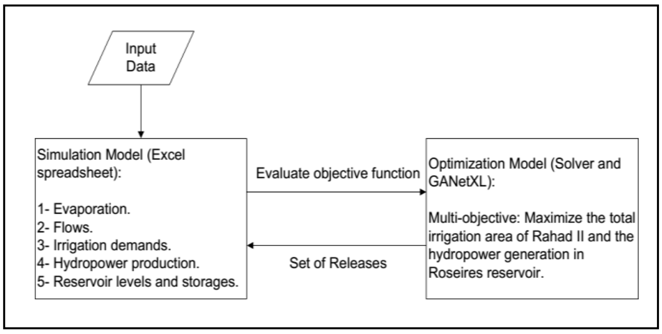

Figure (3): Coupling the optimization with the simulation model of EBSOM

2.2 EBSOM Inputs

In order to simulate the system, the following were represented mathematically:

i) The crop water requirements of all the existing irrigation schemes in every 10-day period: depending on the type of crop, the irrigated area and the time of irrigation.
ii) The "New" Rahad II crop water requirements, by assuming that it will use the same pattern of cropping as Rahad I, This scheme will use a separate canal (its water will not go through the turbines of Roseires, thus will not contribute to the hydropower generation).

iii) The hydropower generation from the turbines by using the power equation, which depends on the flow through the turbines, the turbine efficiency and the head difference of the reservoirs.

iv) Evaporation from Roseires and Sennar Reservoirs in every 10-day period: conditional on the reservoir surface area and the time within the simulation period.

v) The water level and the reservoir storage: by using a stage/level curve.

vi) The change in storage corresponding to the inflow, the evaporation and the release: by using the equation: I – E – R = ∆S.

2.3 Developing GERD Sub-model

Based on existing literature [3] [4], Ethiopian government sources say that GERD's power houses is equipped with 15 Francis turbines; each one to produce 350 MW, which gives a total installed capacity of 5,250 MW. Other sources, [1] [5] [6], say that it will consist of 16 Francis turbines; each one to produce 375 MW, which will give a total installed capacity of 6,000 MW. In this model, 15 turbines with a total installed capacity of 5,250 MW has been taken as GERD's power houses equipment.

The minimum operating level (MOL) and the full supply level (FSL) are reported to be 590 m and 640 m respectively, where the bed level is 500 m. Although the total installed capacity is 5,250 MW, the total electricity production of this dam is expected to be 15,128 GWh on an annual basis. These figures have been communicated in the Ethiopian state owned media repeatedly [5]. This equates into a load factor of 33%, which comes from dividing the total average energy a plant produces during a period time by the amount of energy the plant would generate if operated at full production capacity. (15,128 GWh x 100% / (5.250 GW X 365 days x 24 hrs).

Applying a load factor allows the facility managers to regulate production based upon fluctuations in power demand, as well as ensure that power production is relatively constant with time.

In this study, the operation rule for GERD is by making GERD generate the maximum possible firm energy production. The GERD's operation has been developed as a sub-model in EBSOM. Its output - which is GERD's downstream release - becomes the input for EBSOM replacing Eddiem's natural flow.

GERD's sub-model was developed with some assumptions as follows:

- The natural flow of the Blue Nile to GERD is same as the one reaching Eddeim station before GERD.
- The same three scenarios of natural flow were taken: a dry year, an average year and a wet year.
- GERD will generate, more or less, constant energy (firm energy) with a plant load factor of 33%.
- The water will go only through the turbines when the upstream level is not at FSL (Full Supply level).

The effect of the operation of GERD at the Blue Nile under the three flow scenarios (dry, average and wet) are presented in Figure)4), Figure (5) and Figure (6) respectively.

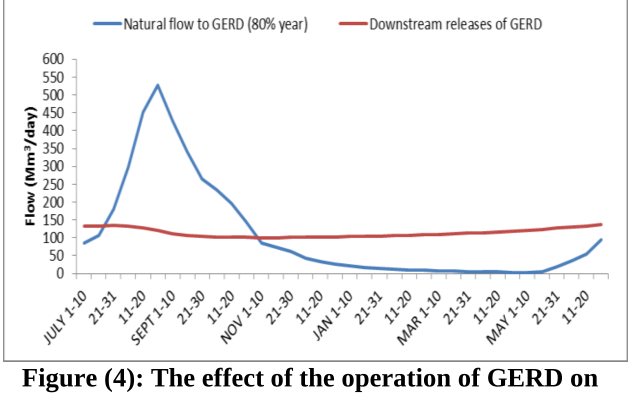

Figure (4): The effect of the operation of GERD on the Blue Nile in the scenario of a dry year (80% year)

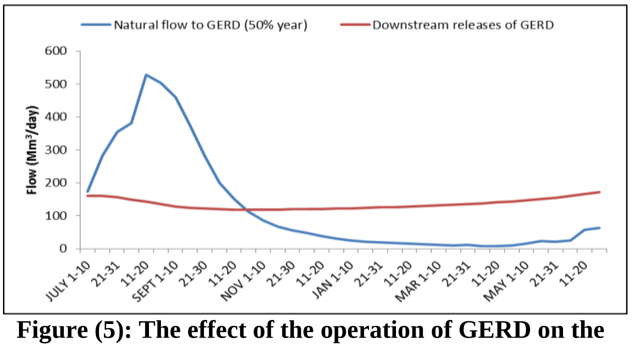

Figure (5): The effect of the operation of GERD on the Blue Nile in the scenario of an average year (50% year)

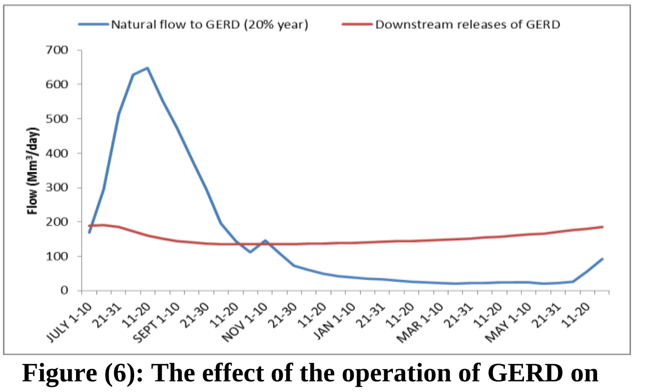

Figure (6): The effect of the operation of GERD on the Blue Nile in the scenario of a wet year (20% year)

The downstream releases of GERD serve as the inflow to Roseires reservoir EBSOM.

2.4 EBSOM after GERD becomes operational

Based on the results of GERD's sub-model, the release varied between 90 Mm3/day and 200 Mm3/day throughout the year. This is much less than the flow after the flood when Roseires reservoir is to be filled (before GERD). GERD is also expected to trap a considerable amount of silt. Hence the filling criteria of Roseires will not be applicable after GERD anymore and filling of Roseires could be done at any time. This means that EBSOM is run for a period of one hydrological year (from the first period of July until the third period of June) which is presented in 36 10-day period time steps. Before GERD, reservoirs that are fed by the Blue Nile (Roseires, Sennar) and the River Nile (Merowe) are filled during the flood period (August, September and October). Egypt's Aswan Dam also depends on the flow during the flood period.

After the operation of GERD, the daily minimum downstream release of Sennar Dam could become 20 Mm3/day to satisfy Merowe's demands and the entire reach from Roseires to Merowe.
The total annual flow of the Blue Nile downstream of Sennar should not be less than 32 billion cubic meters to cover Egypt's demands, which are annual demand instead of daily demands.

These figures are calculated as shown below:

- Based on the Nile Water Agreement of 1959, Egypt's total demand from Sudan is 65.5 billion m^3 annually, which is 55.5 billion m^3 for Egypt and 10 billion m^3 for evaporation at Aswan High Dam [7] [8] [9].
- The River Nile has two main tributaries (Blue Nile and the White Nile) and one small tributary (Atbara River). The White Nile's normal annual flow at Khartoum (1912-1989) is 26.4 billion m^3 and that of Atbara River at its confluence with the Nile is 12.1 billion m^3. This sums up to become around 38.5 billion m^3 [10].
- By taking into consideration that there are evaporation losses and transmission losses on the river reach between Khartoum and Aswan Dam, and that there are some small irrigation schemes depending on this reach, then it is safe to assume that the annual flow from Khartoum to Aswan will be decreased by roughly 5 billion m^3 [2].
- This means that the total annual Blue Nile downstream of Sennar should be around 32 billion m^3 to cover Egypt's demands.
- The 20 Mm^3/day gives the Blue Nile river reach and the River Nile reach an adequate level for the pumps that are used for water supply to the irrigation projects and it is also sufficient for navigation use.

3 Optimization of EBSOM

In this study, Roseires reservoir needs to be optimized for both irrigation and hydropower generation. The maximum area to be planted for Rahad II irrigation scheme needs to be determined and the corresponding hydropower generation needs to be calculated.

With this formulation EBSOM essentially needs to solve a multi-objective optimization (MOO) problem, but it was structured as a Single-Objective optimization model. This is achieved by applying several constant areas of Rahad II - which will act as cases - and running the optimization process to get the maximum hydropower generation without violating some additional constraints.

Two optimization techniques were applied in EBSOM, the Generalized Reduced Gradient (GRG2) Algorithm, which is a Non Linear Programming (NLP) method, and the Genetic Algorithms (GA), which is an Evolutionary Algorithm (EA). The Generalized Reduced Gradient (GRG2) Algorithm was applied by using Microsoft Excel Solver and Genetic Algorithms (GA) was performed by using GANetXL software.

3.1 Mathematical Model Formulation

The objective function (Z) for this single-objective optimization is therefore the maximization of the total annual energy production (P).

$$Z = \mathrm{MAX}\sum_{t=1}^{n} P_t = \mathrm{MAX}\sum_{t=1}^{n} R_t * (G_{us} - G_{ds})_t * \alpha$$

The above objective function is subjected to the following constraints and bounds:

$$G_{MOL} \leq G_{us_t} \leq G_{FSL}$$
$$R_t \geq D_t$$
$$P_t \leq P_{max}$$

Where:
Z = Total annual energy produced in MWh/year.
Pt= Energy production during the period (t) in MWh/day.
Rt = Roseires downstream release for the period (t) in Mm^3.
(Gus - Gds)t = Difference between upstream level and downstream level at Roseires reservoir during the period (t) in meters.
α = the proportionality factor "Alpha"
Gust = Roseires upstream level during the period (t) in m amsl.
GMOL = Minimum operating level of the reservoir in m amsl.
GFSL = Full supply level of the reservoir in m.

Dt = Total daily downstream demands in Mm3/day.
Pmax = Maximum energy that can be produced daily in MWh/day (turbine capacity)
t= 1, 2, 3,..., 24 (before GERD) and 1, 2, 3,..., 36 (after GERD).

There are several constraints and bounds taken into account regarding the optimization:

i) Reservoir Level Constraint:

$$G_{MOL} \leq G_t \leq G_{FSL}$$

ii) Release Constraint:

$$R_t \geq D_t$$

iii) Power Production Constraint:

$$P_t \leq P_{max}$$

3.2 Running the Optimization

A total of 2 Phases containing 12 scenarios and 60 cases were executed by changing the below parameters:

- Three (3) scenarios of hydrological years (dry, average and wet years).
- Five (5) areas for Rahad II scheme (0%, 50%, 100%, 150%, 200% and 250%).
- Two (2) optimization models (SOLVER and GaNetXL)
- Two (2) phases for GERD (before and after)

4 Results

4.1 Scenario (1): before GERD is operated:

In this scenario, when the flow represents the flow of a dry year (80% year), an average year (50% year) and a wet year respectively, both optimization techniques (NLP and GA) were applied in all the 6 cases, which gave 12 solutions represented in 12 feasible points. These feasible points are presented in a Pareto-optimal front shown in Figure (7) below.

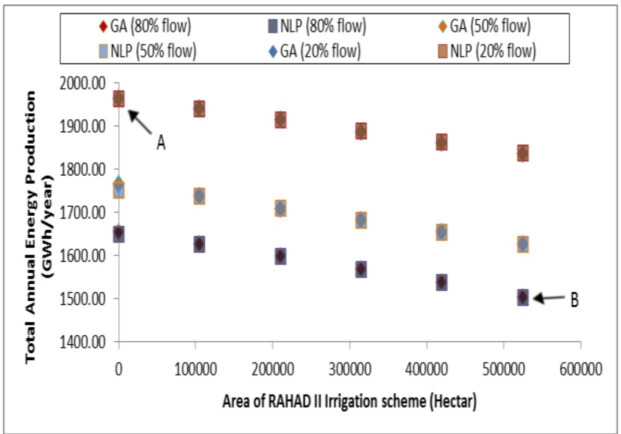

Figure (7): The Pareto-set of all the cases of the phase before GERD becomes operational

* A: The case when the flow is for a wet year and the area of Rahad II is zero (best case scenario from the point of view of hydropower production).
** B: The case when the flow is for a dry year and the area of Rahad II is 250% of the suggested area "525,000 hectares" (worst case scenario from the point of view of hydropower production).

4.2 Evaluation of Scenario (1): before GERD

- From the Pareto-sets shown above, it is observed that both optimization techniques obtained similar shapes of the Pareto-optimal front with the GA method giving a slightly higher value of total annual energy production compared to the solution given by the NLP.
- The difference between the total annual energy production of Roseires reservoir in the best-case scenario from the point of view of hydropower production (which is when the flow is for a wet year and the area of Rahad II is zero) and the worst-case scenario from the point of view of hydropower production (which is when the flow is for a dry year and the area of Rahad II is 250% of the suggested area "525,000 hectares") is 461 GWh/year.
- The results showed that the maximum area to be planted in Rahad II irrigation project was found to be 525,000 hectares, which represents 250% of the suggested area. This area will decrease the annual energy production of Roseires reservoir by the amount of 150.53 GWh/year (9.1%) at minimum and 461 GWh/year (23.5%) at maximum.

4.3 Scenario (2): after GERD is operated:

As mentioned earlier, in the cases after GERD becomes operational, the input of the model would be the downstream releases of GERD when operated under three different scenarios, which are flow of a dry year (80% year), an average year (50% year) and a wet year (20% year)
Figure (8) presents the downstream releases of GERD under the three scenarios.

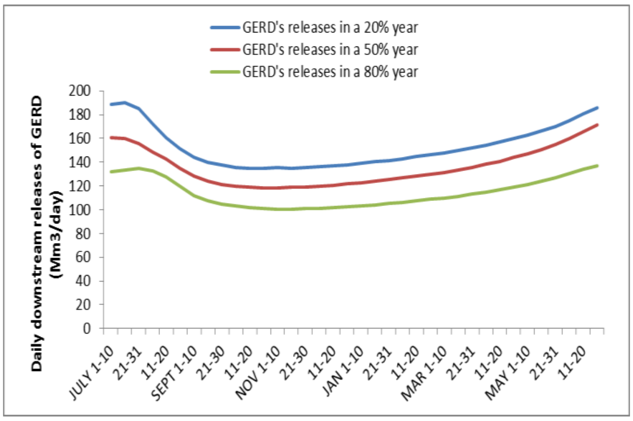

Figure (8): Downstream releases of GERD of a dry year, an average year and a wet year

In this scenario, when the flow represents the flow of a dry year (80% year), an average year (50%
In this scenario, the flow represents the flow of an average year (50% year), both optimization

techniques (NLP and GA) were applied in all the 6 cases, which gives 12 solutions represented in 12 feasible points. These feasible points are presented in a Pareto-set shown in Figure (9) below:

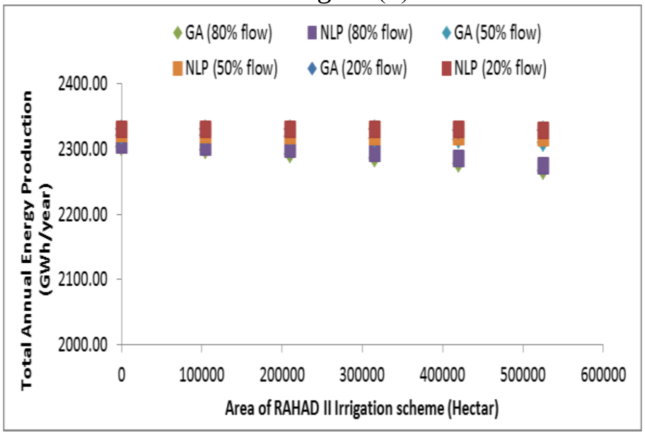

Figure (9): The Pareto-set of all the cases of the phase after GERD becomes operational

4.4 Evaluation of Scenario (2): after GERD

- Both optimization techniques gave generally similar results, acknowledging that the results obtained by the NLP were slightly higher than the ones obtained by the GA, and that the NLP gave a smoother pattern for the upstream levels than the GA.
- The difference between the total annual energy production of Roseires reservoir in the best-case scenario from the point of view of hydropower generation (which is when the flow is for a wet year and the area of Rahad II is zero) and the worst-case scenario from the point of view of hydropower generation (which is when the flow is for a dry year and the area of Rahad II is 250% of the suggested area "525,000 hectares") is only 64 GWh/year.
- The absolute maximum total annual energy generation, which is 2330.16 GWh/year, was reached in several cases. The maximum irrigation area of Rahad II that will cause a critical situation at the reservoirs was not reached. Extending the area of Rahad II more than 250% might lead to that, but such expansion is not practically feasible or possible.
- The difference between the maximum energy and the minimum energy obtained in all these 6 cases is 139.88 GWh/year. This means that if the area of Rahad II is maximized, the total annual energy production of Roseires reservoir will decrease by the amount of 150.53 GWh/year in an average year. The average difference between both GA values and NLP values is 1.7 GWh/year, which represents 0.1% of the average annual energy production of Roseires reservoir of these six cases.

4.5 Roseires reservoir level before and after GERD during three years

EBSOM was run for three hydrological years in order to compare the upstream levels of Rosires reservoir before and after GERD becomes operational. The worst case scenario for all the three years were applied, this was by using the dry year flow (the 80% flow) and an area of 525,000 hectares (250% of the suggested area) for all three of them.

EBSOM was run for the first year, and the final level (level at the end of June) that was generated at the end of the simulation was taken as the first level of the second year, and the same process was applied for the third year.

The levels that were produced for both before and after GERD cases are presented in Figure (10) below:

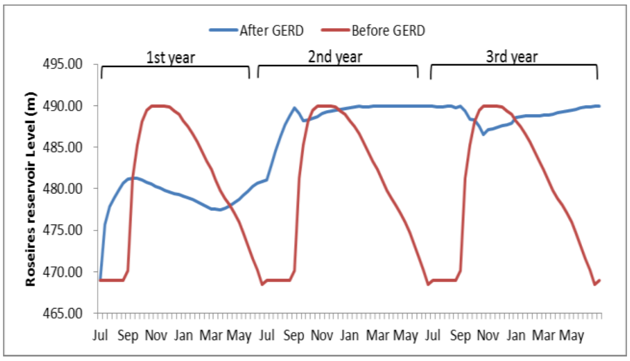

Figure (10): Roseires Levels before and after GERD for a three year period

From Figure (10), several points were noted:

- It was observed that in the case before GERD, the level took the same pattern during the three years. This is due to the procedure of emptying the reservoir during the flood season by reducing the effect of high sedimentation of the reservoir.
- In the case after GERD, the level at the end of every year increased over the previous year, and in the third year the level started at its full supply level (FSL). It then declines in the middle of the year due to the peak demands during that period and comes back to the full supply level (FSL), which is 490 m.
- The pattern of the third year is expected to occur in all the following years to come after that year.
- It is advisable to maintain a free board of 3 meters at least on Roseires reservoir (keeping the level at 487 m instead of 490 m) as a safety precaution to capture any unexpected high flow. This could happen if GERD is at its full supply level (FSL) and received a very high flow.

5 Some Advantages and Drawbacks of GERD to Sudan

5.1 Advantages:

- GERD is expected to regulate the Blue Nile flow that is coming to Sudan. This will give the following benefits:
  a. The flood peaks will be reduced and the droughts will be mitigated.
  b. More hydropower generation from Roseires and the downstream dams.
  c. Cropping intensification can take place due to the availability of water.
  d. The filling of Roseires and all the downstream reservoirs can be delayed.
  e. Enhancement of the pumping of water, navigation on the river and the fisheries due to the high level throughout the year.
  f. In general, more water related projects in Sudan can be implemented.
- GERD is expected to trap a reasonable amount of the sediment, especially during the first years of its operation. This and the regulation of the flow will allow Roseires and all the downstream dams to delay their filling.
- On a broad vision, Ethiopia is expected to generate a colossal amount of energy when GERD operates. In contrast, Sudan can increase their crop production due to the regulation of the Blue Nile. This can lead to a regional cooperation with a mutually beneficial trade between the two countries.

5.2 Drawbacks:

The operation of GERD is expected to have some drawbacks on Sudan. Below are listed some of the possible drawbacks of GERD:

- In the first years during the initial filling of GERD to its active storage, Ethiopia might try to store as much water it can in order to fill the dam in the shortest time possible. This is expected to be damaging to both Sudan and Egypt due to their dependence on the Blue Nile. That is why Legal agreements with Ethiopia are needed to insure that outflow from GERD should always be above the minimum requirements of both Sudan and Egypt.
- GERD might not operate in the same way that was proposed in this study and might affect the operation of all its downstream reservoirs. That is why a joint central operation of all the Blue Nile dams (i.e. GERD, Roseires and Sennar) is needed to acquire the maximum benefits and minimize the drawbacks.
- Even if agreements were made and GERD is operated in the same manner that was exhibited in this study, there are still some drawbacks that are listed below:
  – Groundwater might be affected by the regulation of the Blue Nile flow downstream of GERD. The regulation will decrease the effect of flooding on which the groundwater depends on for recharging.
  – The evaporation of GERD might affect the local climate in that area and the areas around it. It is still not clear if this effect is positive or negative.
  – There are many implications of regulating the Blue Nile river (e.g. a change on the distributions of plants and animals, the fertilization of the soil, etc.).

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