Multiple filling strategies for the Grand Ethiopian Renaissance Dam

Trade-off analyses and suggestions

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Abstract

To analyze the impact of the filling strategies of the Grand Ethiopian Renaissance Dam (GERD) on water and power availability in downstream countries Sudan and Egypt, a system dynamics model of the Eastern Nile Basin is made including the major dams on the Blue Nile, the White Nile and the Atbara River. The purpose of this study is to look for possible trade-offs to minimize water scarcity and maximize power development in the region. The use of water policies, where collaboration between these countries is needed, helps improve the evolution of the area. The GERD can be filled between 77 and 150 months while water scarcity is avoided in Egypt. The filling of the GERD also engages power losses downstream, but the Ethiopian mega dam can compensate for them after 6 month of filling. Sudan is higher exposed to water scarcity than Egypt but has also major advantages of the GERD. After filling, the existing Sudanese reservoirs could generate up to 40% more hydropower in Sudan.

Keywords

Nile River basin, Grand Ethiopian Renaissance Dam, dam filling strategy, system dynamics

Introduction

Since Ethiopia has announced the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile river in 2011, tensions in the Nile river basin are at their highest. This pressure has been caused by high Nile water dependence of downstream countries Sudan and Egypt. But the dam also has major advantages for the whole area because of the 6.000MW annual power generation (Tesfa, 2013; King & Block, 2014) that could help electrification of millions of civilians, attract new industries to the region and maybe export electricity to Europe (EDF & Scott Wilson, 2007; Cascão & Nicol, 2016).

Ethiopia is the world’s fastest growing economy (Shiferaw, 2017; The Economist, 2021) and to continue its development it will need the power generated by the GERD. Ethiopia has the ambition to connect 65% of its population to the electricity grid in the next 5 years and they also want to become the largest electricity exporting country of the Nile basin (Hammond, 2013). The country wants to reach these two goals as soon as possible.

On the other hand, 95% of the water use in Egypt and Sudan comes from the Nile which comes for 57% from the Blue Nile in Ethiopia (NBI, 2012; Arseno, 2007).

In this conflict of interest, Ethiopia wants the power, Egypt and Sudan want the water; the negotiations between these countries are leading to a dead end based on distrust after the construction of the GERD, being finished in 2016 (Aljefri et al., 2019; Al Jazeera, 2020).

A willingness to cooperate was signed by the countries (DoP, 2015) but currently there is no institutional binding agreement signed yet. The major disagreement in these negotiations is how to fill the dam. In 2013 an international and independent panel of experts indicated the need for further research on potential filling strategy of the GERD (IPoE, 2013). In the following years several studies were published to find a way to fill the 74BCM reservoir of the GERD as fast as possible without letting downstream countries remain in water scarcity (Bates et al., 2013; King & Block, 2014; Mulat & Moges, 2014; Zhang et al., 2015; Keith et al., 2016). None of these researchers included the trade-off between power and water due to the lack of infrastructure at the time of their research.
To start filling the GERD it is very important to consider several conditions that influence downstream water scarcity. For example, the Blue Nile flow fluctuates heavily between dry and wet seasons (NBI, 2012; Arseno, 2007). Considering the differences in monthly water flow, the most important conditions to evaluate are the month in which filling is started and the initial volumes of the dam reservoirs in downstream aereas.

Infrastructure
The aspect of power production of the GERD and other downstream dams was taken into account in the research of Wheeler et al. (2016) but there was no possibility to make a clear trade-off (water for power) between Ethiopia and downstream countries due to the fact that there was no joint electricity infrastructure on either side of the frontiers (Block & Strzepek, 2010; MIT, 2014; Salman, 2016). In 2016, Egypt, Ethiopia and Sudan agreed on investing in a common electricity infrastructure to open the possibilities for export and diminish the system's asymmetries in the power grid (Eastern Nile Technical Regional Office (ENTRO), 2016; Cascão & Nicol, 2016). At the moment there is already a 1.000MW (with potential up to 3.000MW) interconnection between Sudan and Egypt (PIDA, 2018; Egypt Independent, 2020) and up to 4.000MW interconnection between Sudan and Ethiopia (PIDA, 2017).
Now being owners of this new infrastructure it becomes more interesting for Egypt and Sudan to import electricity from Ethiopia. If Egypt and Sudan start to import electricity, they will not need the same amount of water in their dam reservoirs like the HAD or the Merowe dam (Sudan) because they have to generate less power. Thanks to the import of electricity, Egypt and Sudan can release more water from their dam reservoirs to diminish water scarcity without losing power. With the new high power interconnections another filling strategie can be considered by creating a balance of power and water in the Nile Basin.

Study objective
This research consists of making a system dynamics (SD) model of the water flow through the Nile river basin and the power production by dams during the next 40 years under 108 filling scenarios and 200 climat replications. The model's aim is to be used to answer the following questions: How does the filling of the GERD affect the total amount of water and power in the Nile River basin under different filling strategies and water scarcity policies? Under what circumstances does the GERD not compensate for power loss in downstream countries? Are there possibilities to make a trade-off between water availability and power generation?

Background, area study and water data

Geographical description
The Nile is one of the world's longest rivers with 6.690 km and has the second largest basin of all Africa with 3,25 million km^2. This mythical river flows through 11 countries (Burundi, Democratic Republic

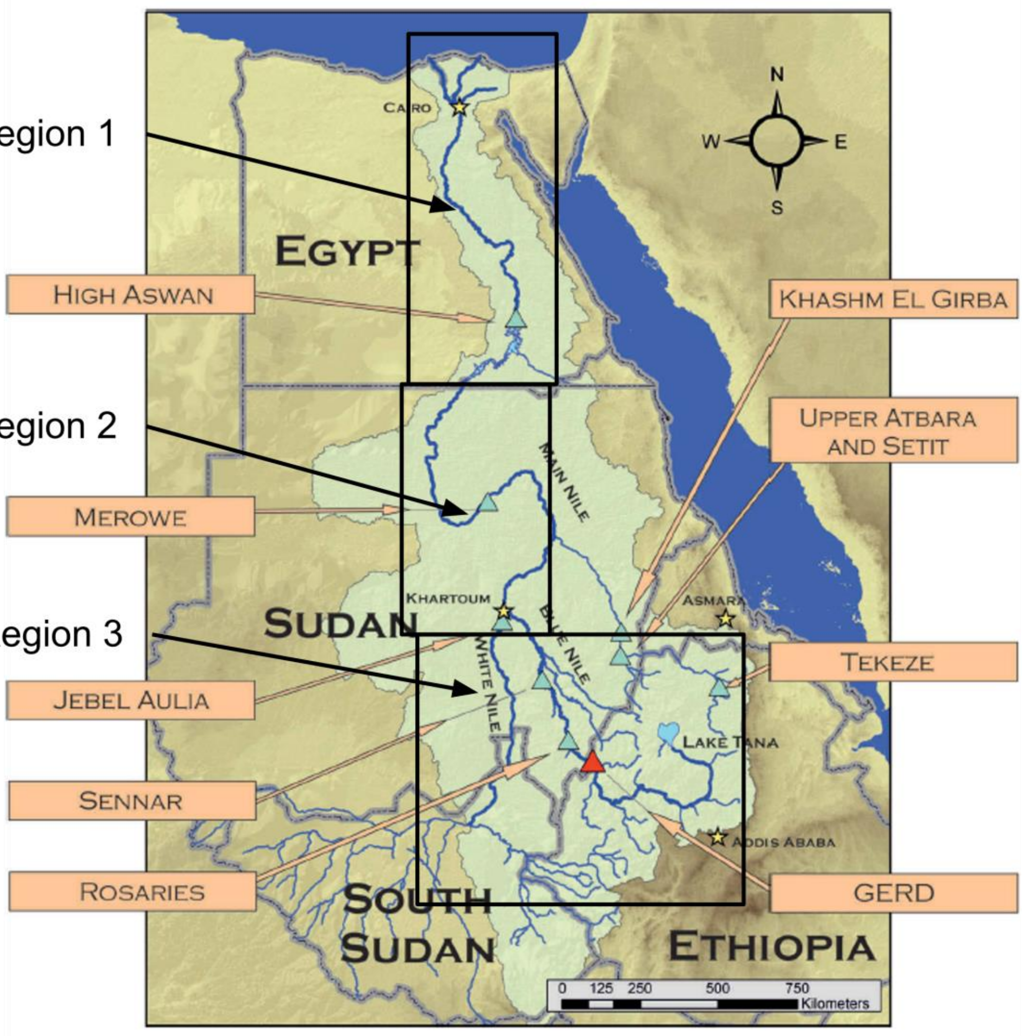


Figure 1a: Map of the Nile basin with the model dams, rivers and climate regions (Keith et al., 2016 & Wheeler et al., 2017)

Figure 1b. Zoom in on the small contributors of the Blue Nile and the Atbara River

of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda) and has many other rivers who contribute to its main flow. This study focuses on the north-eastern part of the river. In this area, the main rivers are the White Nile originating in Uganda's Lake Victoria, the Blue Nile originating from the Ethiopian highlands (Lake Tana), the Tekeze River and the Atbara River (or black Nile) also originating from Ethiopia. In the eastern Nile basin there are also three smaller rivers, the Dinder, the Rehad and the Mareb river. In the analysed area are nine different dams. An overview of the area is given in Figure 1a. An overview of the smaller rivers is shown in Figure 1b. The White and Blue Nile are joining in Khartoum, the capital of Sudan. At this junction the Main Nile starts and is later joined by the Black Nile.

Function per dam

On the White Nile there is only the Jebel Aulia dam (JAD) which is used to control the flow of the river to have a constant inflow at the High Aswan dam. The JAD is used for power generation and irrigation and has a release of 24,5 BCM/year into the Main Nile (Basheer & Elagib, 2018).

On the Blue Nile there are several dams, the first one is the GERD, this mega dam has a power potential of 6.000 MW. Different studies show a variation of average yearly flow between 47 BCM/year and 54 BCM/year with an average of 50 BCM/year at the GERD location. This is based on water measurement between 1912 and 2011 (Abtew & Dessu, 2019; Whittington et al., 2015). On the Tekeze and the Atbara River are three dams. Firstly, the Tekeze dam, this is an irrigation and power dam with a potential of 300 MW (Abera et al., 2018). Secondly the Upper Atbara and Setit Dam (UAS) is a twin dam complex which controls the junction of the Upper Atbara River (5,4 BCM/year) and the Tekeze river (4,4 BCM/year).
The last dam on the Atbara River before it joins the Main Nile is the Khashm el Girba dam (KGD). Like the Sennar dam, this is an irrigation dam (Digna et al., 2018). Due to some rainfall in the region and the contribution of the Dinder, the Rehad (3 BCM) and the Mereb River (0,3 BCM), the yearly contribution of the Atbara River into the Main Nile is about 11,4 BCM/year. This leads to an average inflow of 95 BCM into the Main Nile to the Merowe dam (63% from the Blue Nile, 25% from the White Nile, 12% from the Black Nile (Mulat & Moges, 2014; Zhang et al., 2015; Keith et al., 2016)

The Merowe dam is the largest power production station from Sudan. It has a capacity of 1.250MW and a small irrigation capacity (Teodoru et al., 2006). The last analysed dam of the region is the High Aswan Dam with the world's biggest artificial lake, Lake Nasser. When the Nile flow arrives at this point, according to the Nile water treaty of 1959, 18,5 BCM/year are allocated to the Sudanese part of the reservoir, 10 BCM/year are lost to evaporation in the Main Nile (from Khartoum to Aswan) and 55,5 BCM/year are allocated to Egypt (El-Rawy et al., 2020; Nile Treaty, 1959). In the 1959 treaty it is also indicated that Sudan will not use more than 25% of the total flow of the Nile River and its contributors. The HAD has a power capacity of 2.100 MW and is used for flood protection and irrigation schemes in Egypt. In Figure 2 an overview of the inflow in the Main Nile is shown.

Climate

The region is also divided into three climate zones (Figure 1a). The following assumptions were made:

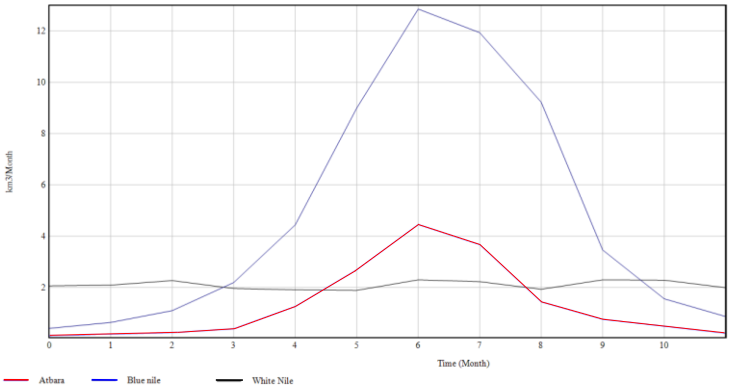


Figure 2: inflows of the Blue Nile, White Nile and Atbara River over one year.

In region 1, Egypt and the East part of the Sahara, there is hardly any precipitation and the temperature could increase by 5 to 7 degrees in the following 40 years (El-Din, 2013; Niang et al., 2008). This will lead to 16% more evaporation at Lake Nasser (Wang et al., 2018).
Region 2, north Sudan, is mainly part of the Sahara. Like region 1, the assumption that there is no rainfall will also be made here. The difference is that the increase of temperature and evaporation will be less severe. According to Elshamy et al. (2009) and Niang et al. (2008) the temperature will rise by 2-5 degrees in this region until 2060. This will lead to, according to the Monteith equation (1981), 8mm more evaporation (this means 7% increase at Merowe Dam).
Region 3 consists of southern Sudan and the Ethiopian Highlands where the Blue Nile originated. This region is equatorial and has cyclic rain levels, the wet season in Ethiopia is between May and September.
Depending on the sub basin, rainfall varies. The GERD sub basin rainfall varies between 1.050 to 1.550 mm on a catchment area of 195.000 km^2 and a catchment rate of 19% (FAO, 2012; International River, 2013; Abtew & Dessu, 2019). The Roseires dam and the Sennar dam have a catchment area of 210.000 km^2 and 87.000 km^2 and an average rainfall of 700mm/year with a catchment rate of 13% (King & Block, 2014; Digna et al., 2014; FAO, 2012; Bashar & Mustafa, 2009). The Tekeze dam and Upper Atbara River have a catchment area of 29.000 km^2 and 45.000 km^2 with also a catchment rate of 13% and an annual rainfall between 600 and 1200mm (FAO, 2012; Abera et al., 2018; Gebremicael et al., 2017). Also, the catching area of the KGD reservoir (Khairy et al., 2019), 45.000 km^2, is generating 1220

mm of rainfall per year. Research by Giannini et al. (2008), based on the precipitation changes in the period of 1950 to 1990, showed precipitation scenarios for eastern Africa. On average, rainfall will increase with 7,5% between 2020 and 2060, it is also possible that rainfall can drop with 5%. The maximum rain increment is 20%. The division of these scenarios of precipitation of this region is shown in Figure 3.

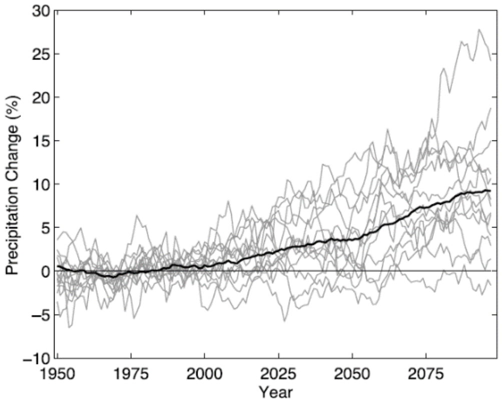


Figure 3: Rainfall prediction in the twenty-first century in eastern Africa (Giannini et al. 2008).

Previous studies

In earlier research, the following methods were used to make estimations for a GERD filling strategy: Bates et al. (2013) made a scenario analysis and a deterministic model of the basin to find that the GERD needs to release 20 to 40 BMC per year depending on the severity of drought. King & Block (2014) had a more climatic approach on the filling by making a rainfall-to-runoff hydrology model for the next 50 years (economic life of a dam) and created several deterministic filling strategies based on percentage of the rainfall in Ethiopia.

Mulat & Moges (2014) made a Mike Basin simulation model to look at the water and power flow between the GERD and the HAD. They concluded that there will be a power reduction of 7 to 12% at the HAD but that the loss of power due to diminished water will lead to 22% less evaporation in Lake Nasser (reservoir of the HAD). Zhang et al. (2015) used a water balance model that estimated the losses of water for the HAD at 7% after 5 years based on a stochastic variation of rainfall.

Keith et al. (2016) made a SD model of the entire Nile basin to find an annual filling rate of 8 to 15% to minimise the impact on Egypt and Sudan.

In the research of Wheeler et al. (2016) they used the RiverWare platform to test several policies to keep downstream countries with sufficient water and the evolution of power in the area while filling the GERD. Zaniolo et al. (2020) made a case reconstruction study to analyse and optimise the filling strategy of the Gibe III dam between Ethiopia and Kenya.The study demonstrates the impact of the filling of the dams in different seasons. All these studies used water elevation as measurements for the amount of water in dam reservoirs. This is because water elevation has a major impact on power production.

Methods

Modelling

In this research a system dynamic (SD) approach with the Vensim Modelling System (Ventana, 2010) will be used. This is a modelling and simulation method to describe, model, simulate, and analyse complex issues or systems in a dynamic way; more specifically when the systems or issues are characterised by feedback, delays and accumulation effects (Forrester, 1961; Sterman, 2000; Pruyt, 2015). An overview of these effects is given in Figure 4.

The flow in the middle of Figure 4 is representing the Blue Nile, the flow at the top of the Figure represents the White Nile and at the bottom of the Figure the Tekeze and Atbara rivers are represented. At the Merowe dam the three rivers join and form the Nile which flows to Lake Nasser in Egypt, the endpoint of the model. The model will run monthly between 2020 and 2060.

Each stock reservoir is an accumulation of water with a balancing feedback loop between the power production, the amount of water in the reservoir and the amount of water released from the dams. Through every flow there is a delay before the water flows into another reservoir.

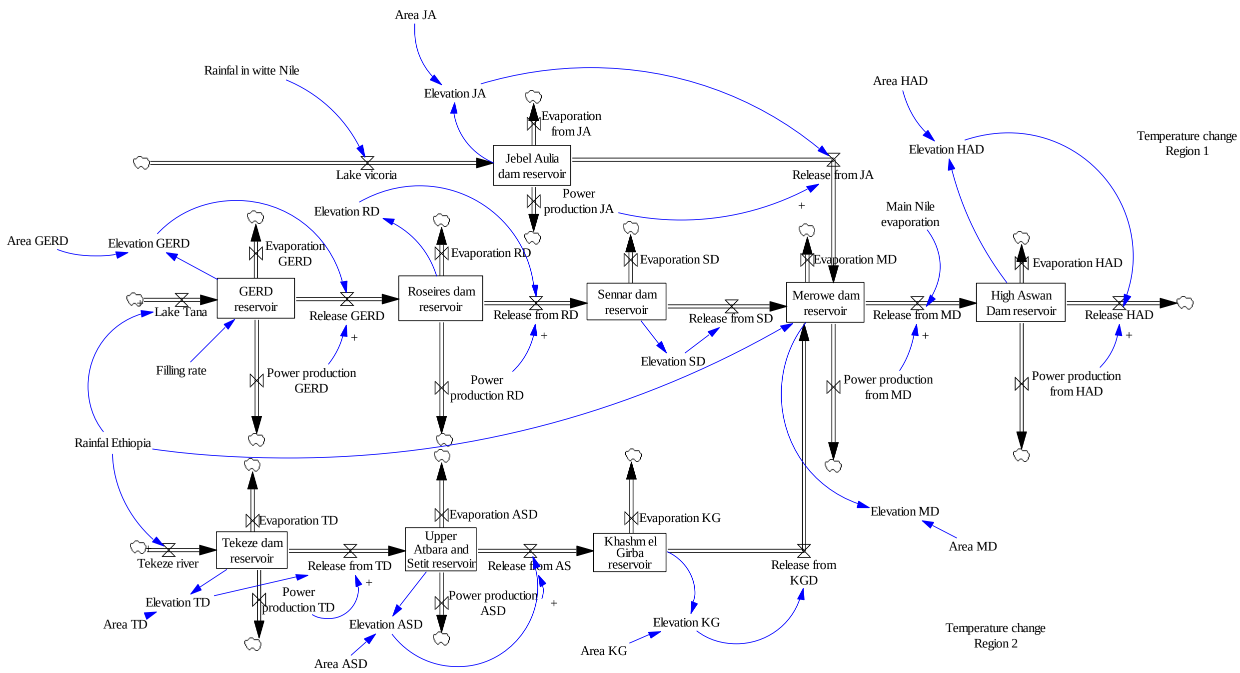


Figure 4: Stock flow diagram of the power and water flows through Ethiopia and Sudan towards the High Aswan Dam in Egypt

Assumptions

1. Every dam filling project has two stages, the first is to fill the reservoir behind the dam up to the level where it can produce power (minimum level of operation (FSL)), the second is to fill the reservoir completely to obtain maximum power production (full level supply (FSL).
2. During the filling of the GERD, Ethiopia will adhere to the Nile water treaty of 1959.
3. Reservoirs will not get smaller in the next 40 years due to sedimentation.
4. In the model only rainfall contributes to the rivers.
5. Irrigation demand remains constant.
6. Every water release is passing by the turbines of the dam to generate power. The only exception is during the wet season, when the inflow is too high for the size of a dam reservoir. In these specific situations the dam is releasing water without generating power.
7. The percentual monthly division of the yearly precipitation is constant

Data use in model

Flows and rain

All the water flows are generated from precipitation data except from the White Nile. The White Nile is originating in Lake Victoria and this climate zone is falling out of the scope of the model. The inflow of the only dam on this river, the JAD, is modeled with a triangular distribution of the flows as described by Basheer & Elagib (2018) with a minimum of 20,8, a maximum of 29,1 and a modus of 23,6 BCM/year. The White Nile is not dependent on seasonal variation like the Atbara River or the Blue Nile so there will be no correction for wet and dry seasons. The research of Giannini et al. (2008) indicated that the amount of precipitation is only increasing in the Eastern part of Africa. Lake Victoria is located in the center of the continent and there are no conclusive predictions forecasting any variation in precipitation in the coming decades.
The rainfall in the Blue Nile and Atbara River sub basin is also generated triangularly on a yearly basis. An overview of the input parameters for rainfall is given in table A1 of the appendix. The seasonal variation is corrected with a lookup table. Wet seasons are the longest in the GERD sub basin (May to September). In the Tekeze and the Upper Atbara sub basins wet seasons are shorter (June to August).

Reservoir area and evaporation

Evaporation is dependent on the surface area of the dam reservoir. Therefore, the model used a lookup table according to the volume of the reservoir. The area of the GERD is varying between 522 km^2 at

MOL and 1883 km^2 at full level supply FSL (Abtew & Dessu, 2019). The area of the HAD is varying between 3800km^2 at MOL and 6.000 km^2 at FSL (Muala et al., 2014). Data for areas of the other dams are shown in tables 2.
The evaporation is also modeled with lookup tables based on the average monthly evaporation calculated with the Penmann equation by Khairy et al. (2019), Vallet Coulomb et al. (2001) and Hassan et al. (2018). An overview of the evaporation coefficients is given in table A3 of the appendix.

Climate change
From Giannini et al. (2008) the assumption was made that after 2000 the variation in rainfall is linear until 2060, due to the fact that rainfall in region 3 in the model was generated by a triangular distribution, the minimum was corrected by a ramp function coefficient decreasing from 0 to 5% over the following 40 years. The modus will increase with the same function from 0 to 7,5% and the maximum will increase from 0 to 20% to make an approximation of the behavior of Figure 3 within the triangular distribution.

The same modeling method is used for extra evaporation in regions 1 and 2. According to Solomon et al. (2007) temperature increases linearly and so does the evaporation (Penmann,1948; Monteith, 1981). The evaporation lookups are multiplied with a ramp function to increase the monthly evaporation coefficients from 0 to 16% in region 1 and from 0 to 7% in region 2. This is an assumed monotonic climate change approach and has a limited sporadic random component. This assumption is based on the 2007 report of the Intergovernmental Panel on Climate Change (IPCC).

Hydrology, reservoirs, and irrigation
Once the flow arrives at the dam reservoir, every dam will retain at least its MOL and release all its excess water at FSL. An overview of the technical characteristics of each dam are given in table A4 of the appendix including turbine specificities.
In contradiction to earlier research, this model uses water volumes to measure water scarcity instead of water elevations in dams. To correct for the loss of power efficiency due to a lower elevation, a volume efficiency correlation has been established for the GERD. At MOL a turbine generates 69% of its indicated power, after that it increases linearly up to 100% at 80% of FSL (Adbelazim et al., 2020). This is assumed for every dam in the model and created with a lookup table dependent on the amount of water in the reservoir. The turbines used in these dams are Francis types and have an efficiency of 95% (Oo et al., 2019; Alvarado, 2009)). Depending on the outflow of the reservoir and the maximum number of turbines in the dam, the amount of turbines the dam could use has been calculated. This way the model can calculate the amount of power for each dam and it also provides for dams to produce more power than their theoretical capacity.

Validation
While simulating, the model is not giving any error signs and the unit check is correct, except for some lookup warnings while calculating the area (in km^2) as function of the volume of the reservoir (km^3). The reason Vensim is giving a unit warning is that a lookup argument is expected to be dimensionless or the time of the simulation.
Every output of the model is dependent on water flows. The amount of irrigation water and power production is a static implementation dependent on the flow stream. Due to the stochastic generation of rainfall to validate the yearly flow of the White Nile, the Blue Nile and the Atbara River, 95% confidence intervals (CI) were created without GERD in place. According to Siam et al. (2017) the standard deviation of stream flow in the Ethiopian Highlands is 7,50 BCM for the Blue Nile and 1,71 BCM for the Atbara River, according to Sene et al. (2001) the standard deviation of the White Nile is 2,41 BCM. In Conway et al. (2017) it is estimated that the standard deviation of the Main Nile is 15% of its runoff, so 14,33 BCM. To validate the water flows some 95%CI were made (Table A5 from the appendix). On the Blue, White and Black Nile the waterflow is slightly below average but the values lay in the 95CI.
To validate the behavior of the model, an extreme value test (Sange and Forrester, 1981) was made by increasing the rain by a factor 1000. Every dam in the model will remain at full level supply and the outflow into Egypt is 4.625 BCM/month. The total generated power is equal to the maximum power potential of the whole system. Also, an extreme value test was made with no rain at all. Every dam reservoir is dropping to MOL at first where it stops releasing water and the total power in the basin drops to zero. Then the water level drops slowly to zero due to the irrigation function that continues providing water for irrigation and other use.

The model will be used between these two extremes. The behavior in these extreme conditions is as expected.

Experimental design

Filling scenarios and how it is modelled

Once the minimum operation level of the GERD (14.7 BCM) is reached, maintaining this level is assumed to take priority over downstream releases due to the high power insecurity the loss of the mega dam will engender. After reaching 3,5 BCM the GERD will start testing its turbines by releasing 270 m^3/s.

Like King and Block (2014) and Keith et al. (2016), the filling of the GERD will be simulated with 5%, 10%, 15%, 20%, 25% and 100% retain rate of the Blue Nile inflow after MOL is reached. This policy will be held until the GERD reaches FSL (74 BCM) for the first time. Afterwards the GERD will release the average Blue Nile flow of 50 BCM/year (or 4,16 BCM/month). In Vensim the change of release policy is modeled with a pulse function. As the IPoE (2013) advised, the impact of the starting volumes in the HAD, the Roseires dam and the Merowe dam will be taken into consideration due to their high influence on the total amount of power in the Nile Basin and their high Blue Nile dependency.

As in Bates et al. (2013) and Wheeler et al. (2016), the starting volume of the dams will be: 80% of FSL because at this point the dam still has maximum turbine efficiency and a common volume in wet season. 65% of FSL, this is approximately the amount of water in the HAD in January, and 50% FSL because this is the amount of water in the HAD during periods of drought.

Water policies

A HAD drought management policy: This is a current existing Egyptian policy when the storage volume in Lake Nasser falls below 70 BCM, the water release will be shortened with 10%, 15% below 65 BCM, and 20% below 60 BCM.

A GERD and HAD coupling: if the amount of water is falling under 45 BCM (20% higher than MOL and 2 month's release reserve before dropping under MOL under HAD the drought management policy). The GERD will release an extra 10 BCM to elevate the amount of water in the HAD. In the paper of Wheeler et al. (2016) it is assumed that the water policies end after the filling of the GERD. In the experiments these policies will be used during the full length of the model.

Both policies are 'one way' policies and affect only one country. Using only one of them will majorly disadvantage one part in the negotiations.

Experiments

To analyze the amount of power generated in the eastern Nile basin and the availability of downstream water the model will be run with every filling scenario, starting time and starting volume will be crossed and simulated with 200 climate replications. This will lead to 108 filling scenarios for the GERD. Depending on the available water and the extra power generated, trade-offs could be identified.

Results

Time to fill the GERD

As can be seen in Figure 6, in none of the climate simulations the GERD can be filled if only 5% of the Blue Nile inflow is retained. To reach FSL Ethiopia will need a higher fill rate. Once at FSL, the GERD reservoir will have between 50 and 74 BMC. An overview of the time needed to fill the GERD is given in Table 1.

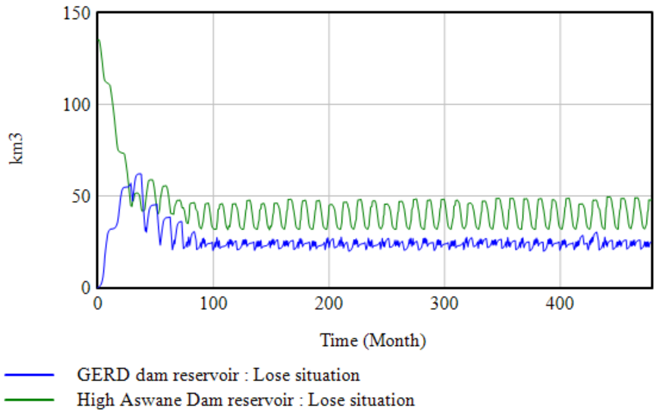


Figure 5: Lose lose situation with only the GERD-HAD coupling in place

If the HAD-GERD coupling only is chosen as water policy, it is not possible to fill the Ethiopian dam. The time that water is released from the HAD to its MOL is faster than the GERD to fill as shown in figure 5, this would be a lose-lose situation. To fill the dam, it is necessary to couple it with the HAD drought

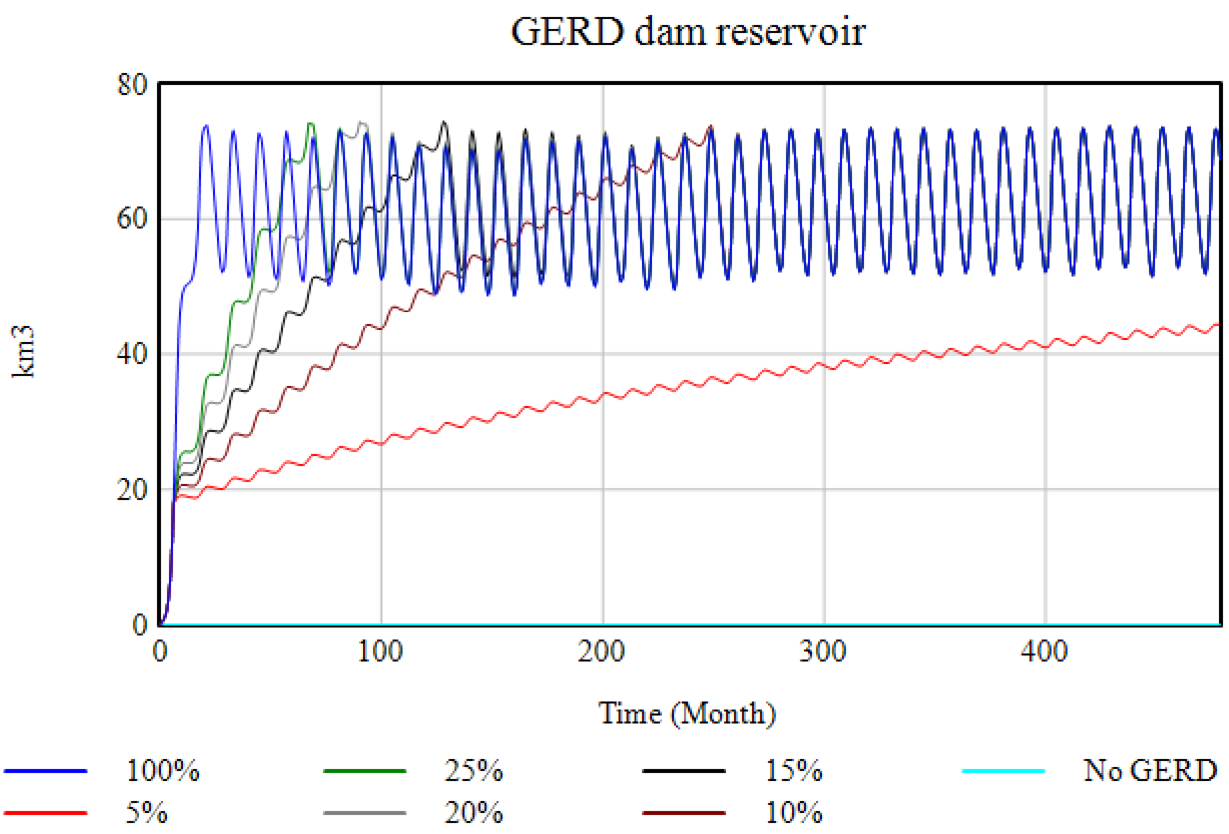


Figure 6: The average volume evolution of the GERD starting to fill under different filling rates and without water policies.

Table 1: Time in month needed to fill the GERD under different filling rates and policies

	No policy or HAD drought management			*GERD - HAD coupling*			*GERD - HAD coupling and HAD drought management*		
Filling rate	*Minimum*	*Maximum*	*Average*	*Minimum*	*Maximum*	*Average*	*Minimum*	*Maximum*	*Average*
10%	*283*	*295,5*	*286,35*	*No filling*	*No filling*	*No filling*	*477*	*477*	*1% filling chance*
15%	*139,5*	*150,5*	*142,27*	*No filling*	*No filling*	*No filling*	*440,5*	*477,5*	*6% filling chance*
20%	*92*	*102,5*	*99,03*	*No filling*	*No filling*	*No filling*	*426,5*	*477,5*	*33% filling chance*
25%	*68,5*	*78,5*	*76,97*	*No filling*	*No filling*	*No filling*	*380*	*478*	*66% filling chance*
100%	*19*	*20*	*19,5*	*19*[1]	*20*[1]	*19,35*[1]	*32,5*	*378*	*197*[2]

[1]Only if the HAD reservoir is filled at 80% FSL, if 65% or 50% is chosen the GERD cannot be filled.

[2] 100% chance of filling the GERD.

management policy and a high filling rate to maximize chances of filling the GERD.

Impact on Lake Nasser and the High Aswan Dam
With the HAD-GERD coupling and the HAD drought management policy in place for the next 40 years, it is less probable that the HAD drops under MOL as in the results of Wheeler et al. (2016). An overview of the risk of water scarcity depending on the initial volume in the GERD and the filling rate is given in Table 2 and Figure 7.
If the filling of the GERD starts in a dry period (50% of FSL of the HAD) there is the highest probability to create water scarcity in Egypt. On the other hand, starting to fill the GERD in a wet season (80% FSL of the HAD) has a large impact on avoiding water scarcity. In any of the simulated runs if both policies are used an initial volume of 65% or higher is sufficient to avoid total water scarcity.
The HAD drought management policy will be able to avoid water scarcity in Egypt up to a filling rate of 20% in wet season. Using a fill rate under 10% will do no harm to Lake Nasser if policies are used. The HAD drought management policy guarantees the best water security for Egypt but has a major impact on water release and has no effect on Ethiopia. The GERD-HAD coupling extends the filling time significantly (Table 1) which is a disadvantage of Ethiopia. A combination of both policies will lead to a sustainable water management. The impact on the filling time will increase but it is possible to fill the GERD with a high fill rate without creating water scarcity if the initial volume is superior to 50%.

Without GERD in place, the average power production, depending on the starting volume, generated by the HAD is 694 GWh/month at 50% FSL, 713 GWh/month 65% FSL, 728 GWh/month 80% FSL. To calculate the amount of power loss for Egypt due to the filling of the GERD, two indicators are analyzed: the average power loss during filling and the average power loss after 40 years. An overview of these power losses is given in Tables A6 and A7 of the appendix.

Depending on the fill rate, the policy, and the initial volume the HAD will lose between 15 and 55% of its power generation. Higher initial volumes will lead to more power losses. The highest power losses occur with filling rate of 20 and 25% (40 to 55% power loss). Low filling rates (5 to 15%) lead to 30 to 40% power loss while filling. A high filling rate (over 25%) causes less power losses (around 20%). This is since there are periods where the HAD is not producing any power due to risks of dropping under MOL.
After 40 years the amount of power produced by the HAD drops by 20 to 35%. This is because Lake Nasser has no possibility of refilling to previous volume.

All these results are combined in Figure 7 to visualize a trade-off overview. Depending on the filling time of the GERD (table 1), the HAD will not drop under MOL and can guarantee water release for Egypt. To avoid (0%) water scarcity, it is possible to fill the GERD in 77 (water scarcity risk of 0,5%) to 150 months. This will lead to 23 to 35% power loss in Egypt during the filling. This is not the optimal outcome but every scenario that has less power loss leads to 100% water scarcity. The long-term power loss of this filling time is 22 to 26%. The trade-off for Egypt to avoid water scarcity is a non-optima high power reduction while filling the GERD and an optimal high power reduction after 40 years.

Table 2: Percentage of the runs where the HAD is dropping under MOL

	No policy			GERD-HAD coupling			HAD drought management policy			Both policies		
Filling rate	50% FSL	65% FSL	80% FSL	50% FSL	65% FSL	80% FSL	50% FSL	65% FSL	80% FSL	50% FSL	65% FSL	80% FSL
5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10%	36%	29%	14%	0%	0%	0%	0%	0%	0%	0%	0%	0%
15%	100%	100%	91%	2,5%	1,5%	1%	0%	0%	0%	0%	0%	0%
20%	100%	100%	100%	9%	8%	6%	17,5%	6%	0%	0%	0%	0%
25%	100%	100%	100%	100%	100%	100%	98%	92%	0,5%	0%	0%	0%
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	4%	0%	0%

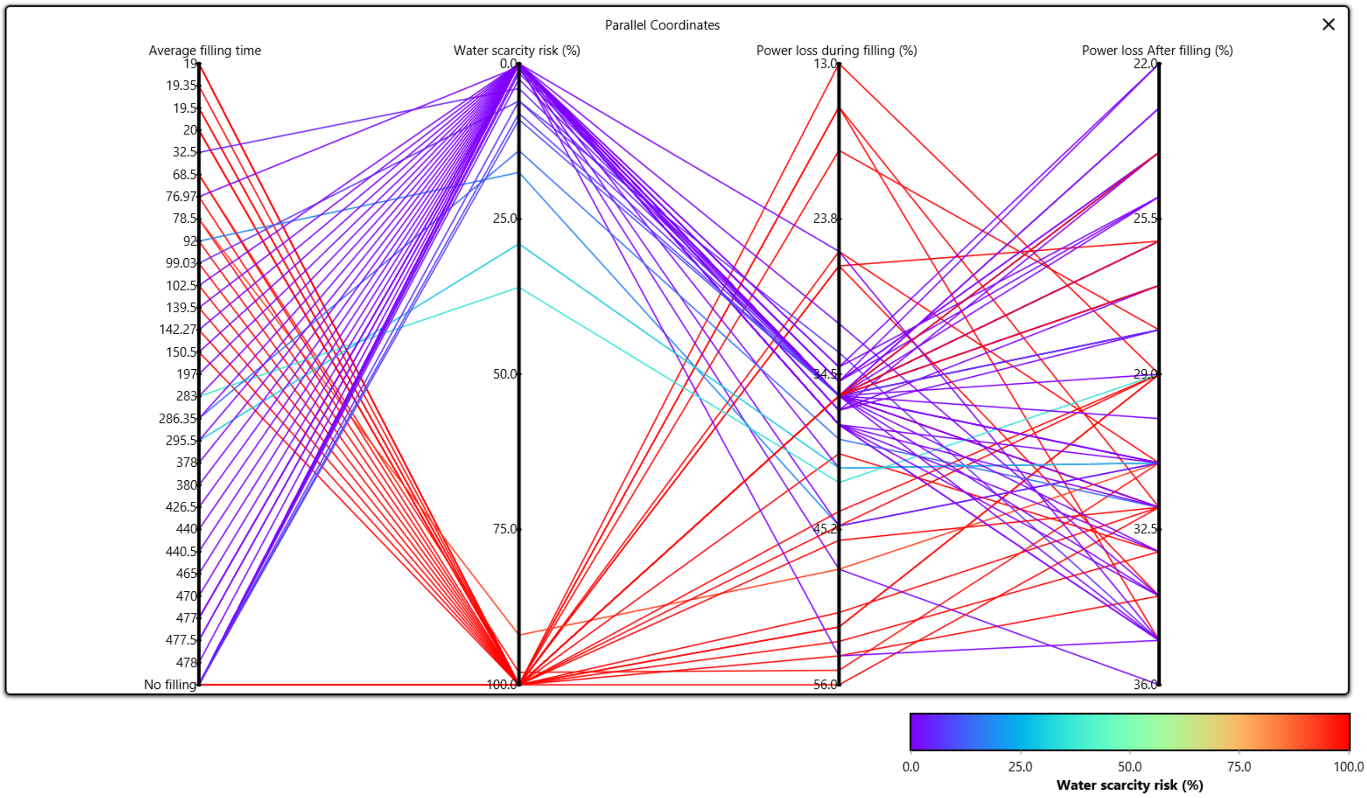


Figure 7: Trade-off overview Egypt

Every purple filling scenario will lead to a water scarcity of 0%. This is set so because 0% water scarcity risk is vital for Egypt.

Impact on Sudanese dams

The filling of the GERD has major advantages for Sudan. Due to the high seasonal variation of the

Blue Nile, the volume of the reservoir of Sudanese dams is very dependent on the season. Table 3 shows an overview of the risks where the Roseires, Sennar and Merowe dams are exposed to dropping under MOL. The filling of the GERD has a negative impact on the water scarcity in Sudan. For every filling scenario that will fill the GERD the Roseires dam is at risk of getting under MOL.

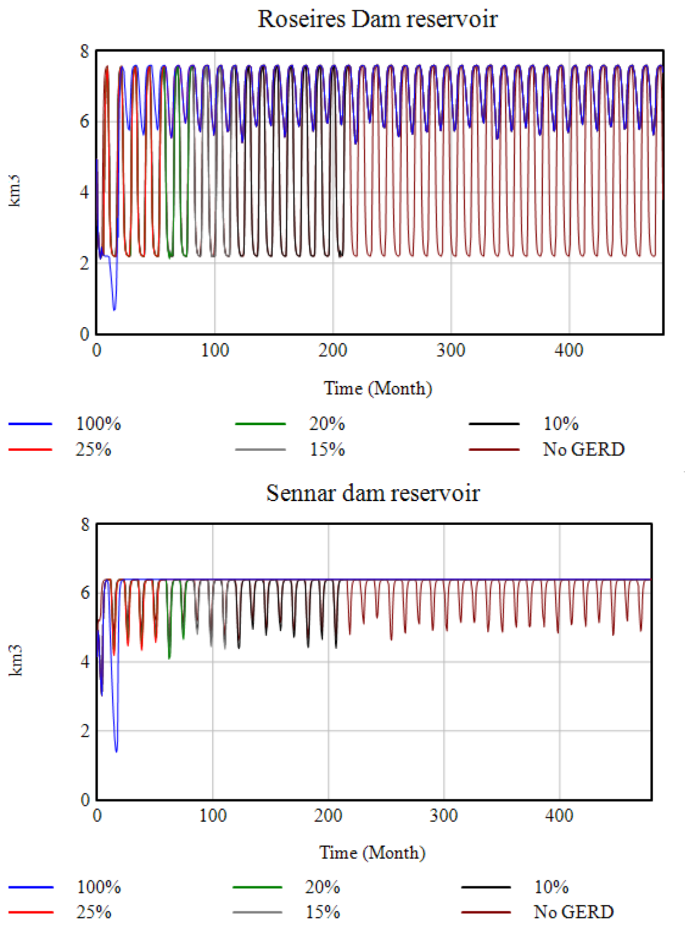


Figure 8: Impact of filling the GERD on the volume in the reservoir of the [a]Sennar Dam and [b]Roseires Dam

Since the Merowe dam is also filled by the White and Black Nile it is less dependent on the Blue Nile and it can operate perfectly up to a filling rate of 10%.

The constant release of the GERD after the filling phase is finished will provide a very stable water inflow in the Roseires and the Sennar dam as can be seen in Figure 8. These dams could nearly permanently stay in full level supply once the GERD is fully operating. The Merowe dam will still be dependent on the wet and dry seasons in Ethiopia.

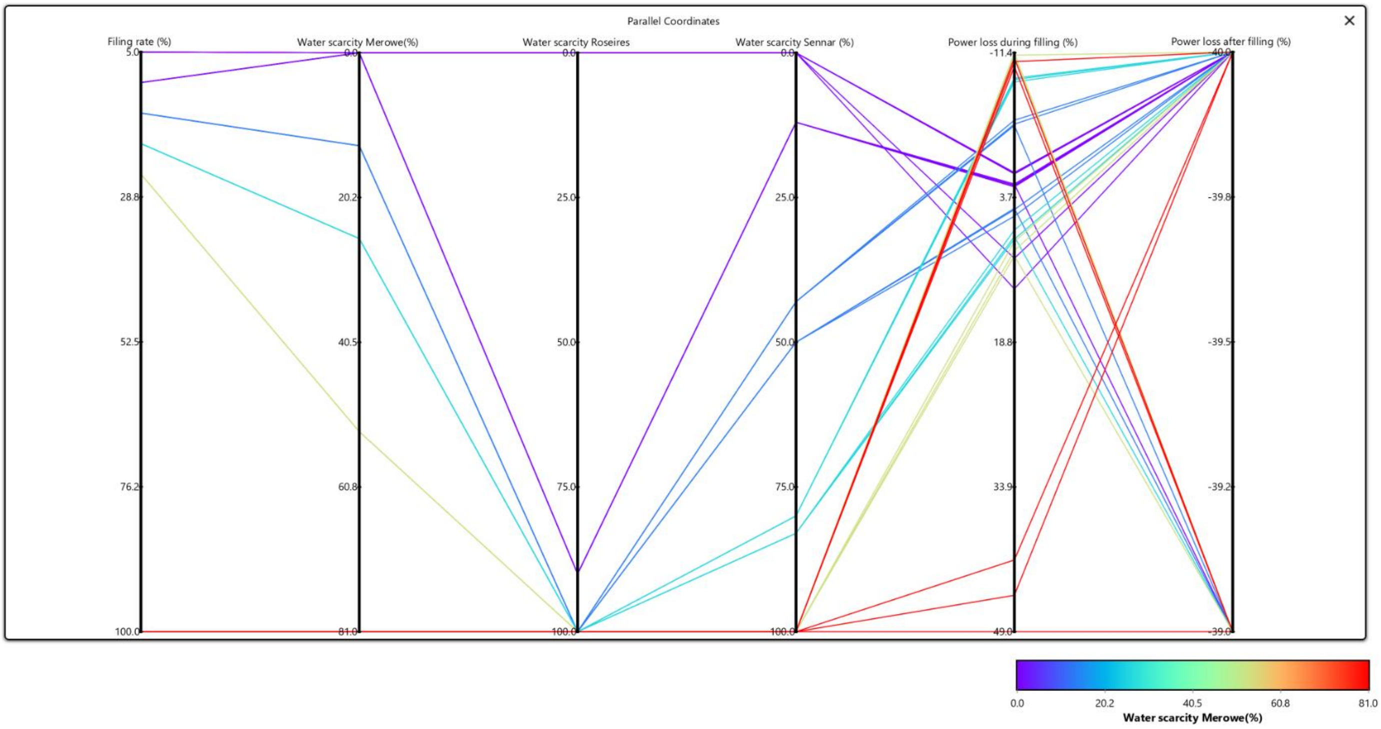
The total power generated in Sudan on the Blue Nile by the Roseires dam and the Merowe dam without the GERD in place is 750 GWh/month independent of the amount of water in the reservoirs. In table A8 and A9 of the appendix is shown how the power loss of the Sudanese dams is evolving during the filling of the GERD.
Despite the high risk of water scarcity with a high filling rate, if the GERD-HAD coupling policy is installed, Sudanese power generation will increase due to the high amount of water released bij the GERD flowing through the turbines of Roseires and Merowe dams to the HAD. This phenomenon starts if a filling rate of 15% or higher is chosen and it could increase Sudanese power from 4 to 11% while filling. Below 15% filling rate, the power generation in Sudan will drop from 1 to 11% dependent on the fill rate. The only possible filling rate where Sudan is not getting water scarcity is 5% (table 3). To improve power and lower the time where Sudan is at water scarcity risk a high filling rate is wishable for Sudan. If no policy is installed, Sudan could lose up to 49% (100% filling rate) of power generation in those two dams. This policy is as important for Sudanese water and power stability as it is for the operation of the HAD and Egyptian water supply.

Once filled, the GERD will improve power generation with 39%. All these outcomes are put together in Figure 9. To avoid water scarcity in Sudan only a low filling rate (up to 10%) can be used. Nevertheless, the amount of hydropower generated by the Roseires and Merowe dams will increase significantly once the GERD is filled. If a low filling strategy is chosen without HAD-GERD coupling Sudanese reservoirs will lose power. If the coupling is created, the Merowe and Roseires dam will increase their production despite the risk of water scarcity. For Sudan this is a real trade-off dilemma to find a strategy that optimizes the filling of the GERD. Wheeler et al. (2016) is speaking of reoperation of these reservoirs to limit water scarcity.

Table 3: GERD filling impact on dam dropping onder MOL in Sudan (% of runes)

	No policy			*GERD - HAD coupling*		
Filling rate	*Roseires*	*Sennar*	*Merowe*	*Roseires*	*Sennar*	*Merowe*
No GERD	*0%*	*0%*	*0%*	-	-	-
5%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
10%	*90%*	*12%*	*0%*	*90%*	*12%*	*0%*
15%	*100%*	*50%*	*13%*	*100%*	*43%*	*13%*
20%	*100%*	*83%*	*26%*	*100%*	*80%*	*26%*
25%	*100%*	*100%*	*53%*	*100%*	*100%*	*53%*
100%	*100%*	*100%*	*81%*	*100%*	*100%*	*81%*

Figure 9: Trade-off overview Sudan



Every purple line means that water scarcity is avoided in the Merowe dam. This is chosen because this dam is the largest power source in Sudan. The filling of the GERD power is more important to Sudan since in nearly every scenario the Roseires dam is dropping under MOL.

Total power in the system

The GERD has a power potential of 6.000MW due to the seasonal fluctuation of the Blue Nile River. As Wheeler et al. (2016) indicated, once filled, the GERD will only under several weather conditions be able to produce more than 2.100MW. Figure 10 can also be understood that the amount of power is nearly doubling (from 1.500 GWh/month average before filling to 3.000 GWh/month on average after

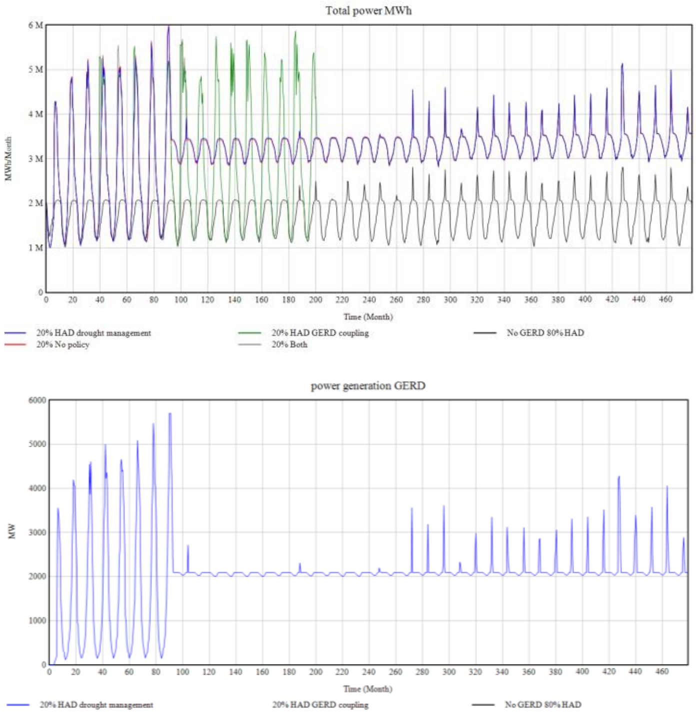


Figure 10: Power generation GERD[a] total power in the system with and without GERD[b].

filling) in the eastern Nile River basin once the GERD has reached FSL. But can the GERD compensate for downstream power loss. For that, a zoom-in on the first two years of the total amount of power in the basin has been made. A view of the 20% filling strategy with different policies is shown in Figure 11. It shows that during the first month the amount of power generated is below the amount of power in a situation without the GERD.

If a filling strategy of 25% or lower is chosen, independent of the initial value of the HAD, the first 6 months after MOL is reached are critical and the downstream power losses are higher than the power generation of the GERD. After this period, due to the new infrastructures, the lost downstream power can be compensated by the GERD to continue its filling. If a filling strategy higher than 25% is chosen the amount of downstream power losses are higher and it will take between 18 and 32 months, depending on the filling policies, to compensate for power losses. In all the scenarios simulated none of them gave a possibility to start filling the GERD without jeopardizing the total amount of downstream power.

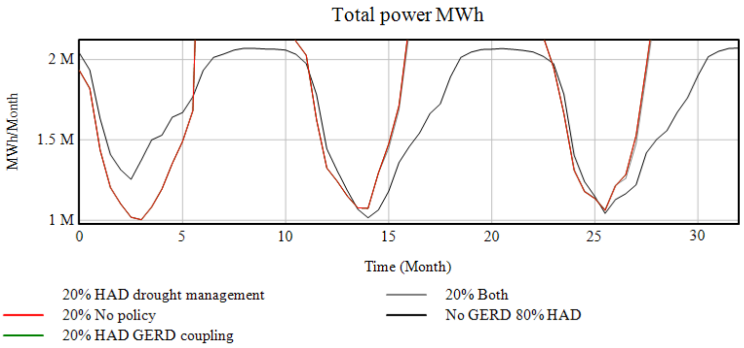


Figure 11: Zoom in of the first two years of the total power in the easter Nile basin under different policies with a filling rate of 20%.

Discussion

The introduction of the GERD will, once filled, double the amount of power into the Eastern Nile basin. With climate change the amount of rain in Ethiopia, the evaporation in Sudan and Egypt will increase which adds extra complexities to the filling of the GERD. The results gave an indication that after 6 months there is a possibility to make trade-offs between water scarcity and power generation between Egypt and Ethiopia. For Sudan and Ethiopia these trade-offs are more difficult to find without reoperating these reservoirs.

This study analyzed trade-offs under several conditions: the initial volume of water in dam reservoirs, the filling rate of the GERD and the impact of two policies: High Aswan Dam drought management and a fixed release form the GERD to the HAD if it is nearly dropping under minimum level of operation (GERD-HAD coupling). To optimize the filling time of the GERD and to avoid water scarcity an implementation of both policies will be necessary.

If at least the HAD drought management policy is used by Egypt and an initial volume of the HAD is 80% of FSL while starting the filling of the GERD, a

filling time of 6,5 years is feasible. If the GERD-HAD coupling is also installed it will take to 12,5 years to fill the GERD with no water scarcity. This is slower than Mulat & Moges (2014) but in their research there is a higher risk of water scarcity in their proposed 6 years filling strategy. On the other hand, the policies have a great impact on avoiding water scarcity so the GERD can be filled faster than the advice of Keith et (2016) to fill the GERD in 11 to 14 years without policies.
Downstream power losses while filling the GERD and afterwards are higher than other studies. In Zhang et al. (2015), with no water policies, estimated the power loss at the HAD of 7% after filling. With policies, this amount can be reduced to 3 to 5%. These results are predicating 22 to 26% power reduction after the GERD has been filled. The model used predict a faster deflate of Lake Nasser than the model of Zhang.
The power losses in Sudan are a subject to discussion. Wheeler et al. estimated around 21% loss if no GERD-HAD coupling was installed and predicted an increase of 28% after filling. While this simulation has more optimistic results (10% loss during filling, 39% win after filling), the Sudanese dams are subject to further investigation on their power potential and their use to avoid water scarcity.
Policies also have several implications. The GERD-HAD coupling will lead to a small reduction of power generation in Ethiopia in the long term but generates high peak power that can be exported to the rest of the Eastern Nile basin or Europe due to the recent increase in infrastructure. The fact that Ethiopia can export the power more easily is a lower barrier to accept this policy. The HAD drought management policy is also important for maintaining the HAD at MOL as long as possible but it could decrease water availability in Egypt for 5 to 15% depending on the severity of the drought. This policy could have major implications on other water infrastructures in Egypt.

This study is based on several assumptions. The most important one is that the model has been built on volumes in reservoirs and not on water elevation like the most research on hydropower. For every dam in the Eastern Nile Basin, it is assumed that their power efficiency according to the volume is the same as the Francis type turbines of the GERD, as described by Adbelazim et al. (2020). The second major assumption is regarding the sedimentation accumulation in reservoirs. This has not been taken into account in this study. It is expected that sedimentation will lead to less power generation due to smaller reservoirs which has been shown, according to Teodoru et al. (2006), a major threat for the Merowe dam because it is located on a junction point between rivers. Further research needs to prove if this phenomenum has significant impact on the HAD or the GERD.
For now, the new subjects for negotiations between Egypt, Sudan and Ethiopia are the implementation of the HAD drought management policy, the filling rate, the initial volume of the HAD, the amount of water release in the GERD-HAD coupling, the determination at which volume this amount should be released in Lake Nasser and a proper way to reoperate Sudanese reservoirs. To answer these questions the model used for this study can be used for further research.

Conclusion and future work

Using both water policies will lead to a longer filing time for the GERD than with no policies at all. The fastest way to fill the GERD without creating water scarcity in Egypt (6,5 years) is with the HAD drought management policy only in place. If both countries use policies to reduce water scarcity, the filling will take up to 12,5 years if the initial volume in the HAD is higher than 80% FSL.
The major water and power results are that the GERD cannot be filled with a 5% filling rate policy or with the GERD-HAD coupling only. A combination of both the HAD drought management policy and the GERD-HAD coupling are the most effective way to avoid downstream water scarcity but can lead to a lose-lose situation where neither the GERD nor the HAD are able to run at full level supply if the filling rate of the GERD is chosen lower than 25%. If the filling of the GERD starts during a dry season (50% FSL), Egypt is exposed to high risk of water scarcity. On the other hand, if the filling starts in a wet season (80% of FSL of the HAD) Egypt is under no condition at water scarcity risk with the HAD drought management policy in place and a GERD filling rate of 20% or less. So proper planning can significantly increase the avoidance of downstream water scarcity.
Once the GERD is operating at FSL, it will double the amount of power in the Eastern Nile basin up to 3.000 GWh/month. The possibility of exchanging power due to new infrastructures reduces power losses in the basin. Nevertheless, the GERD is not

able to compensate for downstream power losses in the 6 first months after the filling has started if a filling rate is chosen below 25%. With a higher filling rate, the GERD will take up to 32 months to re-establish power balance in the Nile River basin.
For Egypt, the trade-off to be made to avoid water scarcity are a loss of power between 23% and 35% while filling the GERD a power loss of 22% to 26% once the GERD is filled. For Sudan, a trade-off is more difficult to find since a filling rate of 10% or higher leads to a large risk of the Roseires Dam dropping under MOL. On the other hand, the GERD will upgrade the efficiency of the Sudanese dam up to 40%. The trade-offs for Sudan are very dependent on the possibility of reoperating these dams to avoid water scarcity.

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Appendix:

Table A1: Yearly minimum, modus and maximum precipitation (in mm) in region 3 based on data from Abtew & Dessu (2019), Whittington et al.. (2015), King and Block (2014) for the Blue Nile, Abera (2018) and Gebremicael et al. (2017) for the Tekeze and upper Atbara river and Digna et al. (2018) and Khary et al. (2018) for the rainfall between dams.

Precipitation location	Minimum (mm)	Modus (mm)	Maximum (mm)
Blue Nile to GERD	1050	1300	1550
Blue Nile to Roseires dam	400	700	750
Blue Nile to Sennar dam	400	700	750
Tekeze River to Tekeze dam	600	1220	2000
Upper Atbara River to UAS	400	600	1200
Atbara river to KGD	400	600	1200

Table A2: Minimum and maximum area of the dams from Hassaballah et (2012) (Roseires and Sennar), Muala et al. (2014) (HAD) Gebremicael et al. (2017) (UAS), Digna et al. (2018) (KGD and Merowe), Abtew & Dessu (2019) (GERD), Basher & Elagib (2018) (JAD) and Abera et al. (2018) ((Tekeze dam)

Dam	Area at MOL (km^2)	Area at FSL (km^2)
GERD	522	1883
High Aswan Dam	3800	6000
Tekeze dam	116	147
Upper Atbara and Setit	145	262
Khashm el Girba Dam	40	130
Roseires dam	100	440
Sennar dam	30	121
Merowe dam	350	800
Jabel el Julia dam	600	1500

Table A3: Monthly evaporation (mm) in every dam reservoir of the model (Khairy et al., 2019; Hassan et al., 2018 and Vallet Coulomb et al., 2001)

	GERD	RD	SD	MD	HAD	JAD	TD	UAS	KGD
January	153.8	181.7	137.3	112.3	109.3	149.4	72.7	96.8	136.4
Februari	162.2	211.5	171.1	197.8	151.5	184.1	94.1	115.1	161.3
March	166.1	262.1	208.5	210.9	185.4	214.0	125.7	131.8	201.5
April	165.6	284.3	235.6	250.5	233.5	225.5	134.8	154.9	233.2
May	170.3	270.3	239.8	273.3	279.8	217.6	168.6	175.9	272.4
June	167.6	206.7	201.5	292.2	297.6	186.9	133.6	145.8	272.4
July	135.8	138.5	145.8	240.2	276.0	127.5	121.1	132.4	189.3
August	137.1	114.4	119.3	215.2	274.2	121.1	98.6	109.3	152.5
September	136.4	121.1	138.2	198.8	245.7	147.6	88.0	98.9	177.5
October	162.4	145.8	146.4	154.6	210.0	152.2	75.8	80.4	151.0
November	161.1	175.3	153.4	159.2	137.1	151.0	66.7	75.8	168.9
December	156.5	172.0	136.7	125.1	100.4	151.0	61.2	47.8	134.2

Table A4: Technical overview of each dam from Digna et al. (2018) for operation levels, Alvarado (2009), Pennacchi et al. (2012), Oo et al., 2019 and El Ray et al. (2020) for the technical overview of turbines.

	MOL (in BCM)	FSL (in BCM)	Maximum turbines	Power turbine (MW)	Water flow (m^3/s)
GERD	14,7	74	16	375	270
High Aswan Dam	31,9	169	12	175	300
Merowe Dam	2,48	12,4	100	120	300
Sennar Dam	0,22	6,4	-	-	-
Roseires Dam	2,2	7,6	7	40	70
Tekeze Dam	4,29	9,9	4	75	175
Upper Atbara and Setit Dam	0,6	2,7	4	40	70
Khashm el Girba	0,1	1,3	-	-	-
Jebel Aulia Dam	0,7	3,5	10	3,5	17,5

Table A5 95% Confidence interval of water flow through the Eastern Nile basin in BCM

River	Theoretical average	Standard deviation	Confidence interval	Modelled average	Conclusion
Blue Nile	54	7,50	[51,68;56,32]	53,68	Valide
White Nile	23,6	2,41	[22,85;24,35]	22,30	Valide
Black Nile	17,9	1,71	[17,37;18,43]	17,53	Valide
Main Nile	94,5	14,3	[90,06;98,94]	94,16	Valide

Table A6: Average power loss during filling of the GERD in the HAD

Filling rate		No policy		HAD drought management policy		GERD - HAD coupling		Both	
		Power loss [GWh/month]	In %	Power loss [GWh/month]	In %	Power loss [GWh/month]	In %	Power loss [GWh/month]	In %
5%	50% FSL	258	37.18%	240	34.58%	249	35.88%	234	33.72%
	65% FSL	266	37.31%	249	34.92%	257	36.04%	246	34.50%
	80%FSL	268	36.81%	252	34.62%	259	37.32%	249	34.20%
10%	50% FSL	291	41.93%	261	37.61%	249	35.88%	246	35.45%
	65% FSL	289	40.53%	270	37.87%	257	36.04%	256	35.90%
	80%FSL	283	38.87%	273	37.50%	260	35.71%	260	35.71%
15%	50% FSL	308	44.38%	251	36.17%	249	35.88%	249	35.88%
	65% FSL	290	40.67%	452	63.39%	258	36.19%	259	36.33%
	80%FSL	265	36.40%	464	63.74%	261	35.85%	265	36.40%
20%	50% FSL	313	45.10%	314	45.24%	251	36.17%	255	36.74%
	65% FSL	317	44.46%	283	39.69%	262	36.75%	257	36.04%
	80%FSL	408	56.04%	241	33.10%	269	36.95%	275	37.77%
25%	50% FSL	364	52.45%	409	58.93%	249	35.88%	257	37.03%
	65% FSL	393	55.12%	388	54.42%	258	36.19%	271	38.01%
	80%FSL	408	56.04%	348	47.80%	263	36.13%	279	38.32%
100%	50% FSL	361	52.02%	357	51.44%	187	26.95%	254	36.60%
	65% FSL	188	26.37%	193	27.07%	138	19.35%	226	31.70%
	80%FSL	114	15.66%	119	16.35%	99	13.60%	191	26.24%

Table A7: Average power loss at HAD after 40 years during filling of the GERD

Filling rate		No policy		Drought management policy		GERD - HAD coupling		Both	
		Power loss [GWh/month]	In %	Power loss [GWh/month]	In %	Power loss [GWh/month]	In %	Power loss [GWh/month]	In %
5%	50% FSL	171	24.64%	152	21.90%	163	23.49%	153	22.05%
	65% FSL	190	26.65%	173	24.26%	182	25.53%	173	24.26%
	80%FSL	205	28.16%	188	25.82%	198	28.53%	188	25.82%
10%	50% FSL	202	29.11%	221	31.84%	165	23.78%	200	28.82%
	65% FSL	221	31.00%	240	33.66%	184	25.81%	217	30.43%
	80%FSL	236	32.42%	255	35.03%	201	27.61%	236	32.42%
15%	50% FSL	202	29.11%	221	31.84%	168	24.21%	206	29.68%
	65% FSL	221	31.00%	240	33.66%	187	26.23%	222	31.14%
	80%FSL	236	32.42%	255	35.03%	202	27.75%	243	33.38%
20%	50% FSL	202	29.11%	221	31.84%	170	24.50%	221	31.84%
	65% FSL	221	31.00%	240	33.66%	189	26.51%	240	33.66%
	80%FSL	236	32.42%	255	35.03%	204	28.02%	255	35.03%
25%	50% FSL	202	29.11%	221	31.84%	168	24.21%	221	31.84%
	65% FSL	221	31.00%	240	33.66%	187	26.23%	240	33.66%
	80%FSL	236	32.42%	255	35.03%	202	27.75%	255	35.03%
100%	50% FSL	202	29.11%	221	31.84%	180	25.94%	221	31.84%
	65% FSL	221	31.00%	240	33.66%	199	27.91%	240	33.66%
	80%FSL	236	32.42%	255	35.03%	214	29.40%	255	35.03%

Table A8: Average power loss in Sudan (Roseires Dam and Merowe Dam) during the filling of the GERD

Filling rate		No policy		GERD - HAD coupling	
		Power loss [GWh/month]	In %	Power loss [GWh/month]	In %
5%	50% FSL	8	1.07%	9	1.20%
	65% FSL	8	1.07%	99	13.20%
	80%FSL	8	1.07%	75	10.01%
10%	50% FSL	19	2.54%	19	2.54%
	65% FSL	18	2.40%	18	2.40%
	80%FSL	17	2.26%	17	2.26%
15%	50% FSL	42	5.61%	-31	-4.14%
	65% FSL	36	4.80%	-30	-4.00%
	80%FSL	37	4.93%	-29	-3.86%
20%	50% FSL	60	8.01%	-63	-8.41%
	65% FSL	58	7.73%	-66	-8.80%
	80%FSL	53	7.06%	-65	-8.66%
25%	50% FSL	73	9.75%	-83	-11.08%
	65% FSL	69	9.20%	-84	-11.20%
	80%FSL	62	8.26%	-86	-11.45%
100%	50% FSL	367	49.00%	-75	-10.01%
	65% FSL	339	45.20%	-79	-10.53%
	80%FSL	312	41.54%	-82	-10.92%

Table A9: Average power loss in Sudan once the GERD is filled

Filling rate		No policy		GERD - HAD coupling	
		Power loss [GWh/month]	In %	Power loss [GWh/month]	In %
5%	50% FSL	-247	-32.98%	-247	-32.98%
	65% FSL	-246	-32.80%	-246	-32.80%
	80%FSL	-245	-32.62%	-245	-32.71%
10%	50% FSL	-298	-39.79%	-298	-39.79%
	65% FSL	-297	-39.60%	-297	-39.60%
	80%FSL	-296	-39.41%	-296	-39.41%
15%	50% FSL	-298	-39.79%	-298	-39.79%
	65% FSL	-297	-39.60%	-297	-39.60%
	80%FSL	-296	-39.41%	-296	-39.41%
20%	50% FSL	-298	-39.79%	-298	-39.79%
	65% FSL	-297	-39.60%	-297	-39.60%
	80%FSL	-296	-39.41%	-296	-39.41%
25%	50% FSL	-298	-39.79%	-298	-39.79%
	65% FSL	-297	-39.60%	-297	-39.60%
	80%FSL	-296	-39.41%	-296	-39.41%
100%	50% FSL	-298	-39.79%	-298	-39.79%
	65% FSL	-297	-39.60%	-297	-39.60%
	80%FSL	-296	-39.41%	-296	-39.41%

Note that the negative numbers mean that the amount of power generated by the Roseires and the Merowe dam is exceeding 750 MWh/month.