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Impact of water resources development on water availability for hydropower production and irrigated agriculture of the Eastern Nile Basin

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Abstract

The Eastern Nile riparian countries are currently developing several reservoir projects to contribute to the needs for energy and food production in the region. In the absence of formal mechanisms for collaboration, the transboundary nature of the Eastern Nile basin makes water resources development challenging. The large seasonal and inter-annual variability of the river flow increases those challenges. This paper assesses the implications of water resources development in the Eastern Nile basin on water availability for hydropower generation and irrigation demands at country and regional levels, using simulation and scenario analysis methods. Twelve scenarios are used to test developments of several dams and irrigation demands, Grand Ethiopian Renaissance Dam (GERD) operation options, and unilateral (status quo) versus integrated transboundary management of dams. A RIBASIM model that included twenty dams and twenty one irrigation schemes was built, using a complete data set of 103 years at a monthly time step. Four indicators have been used for evaluating the performance of the system: hydro-energy generation [MWh/yr], reliability of irrigation supply [%], reservoir net evaporation [10^6 m^3/yr] and flow regimes of rivers [m^3/s]. The results show that in case of managing the system in an integrated transboundary manner and without new irrigation development projects, GERD would increase the hydro-energy generation in Ethiopia by [+ 1,500%], Sudan [+17%] and a slight reduction in Egypt [- 1%]. Supply reliability of existing and planned irrigation schemes in Sudan would practically not influenced by the GERD, but reduces by about 8% when upstream development and new irrigation expansion materialized. Full development of the Eastern Nile basin would reduce the irrigation supply reliability in Egypt to [92%] compared to the base scenario [100%]. Compared to integrated management, unilateral management would increase the hydro-energy generation in Ethiopia [+ 16%], increase the rate of evaporation losses in the basin [+15%] and reduce the irrigation supply reliability in Sudan after full development of dams and irrigation projects [-10%]. Water resources developments would have considerable but varying impacts on the countries.

Key words: *Eastern Nile Basin, simulation models, river basin management, Grand Ethiopian Renaissance Dam, energy generation, RIBASIM*

Introduction

The Eastern Nile basin is the main source of water for the Main Nile River as it drains more than 85% of the total Nile basin runoff estimated as 84 ×10^9 m^3/yr measured at Aswan High Dam (AHD) (Ribbe and Ahmed, 2006). It covers the Blue Nile, Baro-Akobo-Sobat, White Nile, Tekeze-Atbara and Main Nile sub-basins and extends over four countries: Ethiopia, South Sudan, Sudan and Egypt (**Figure**

1). The basin is characterized by a low level of economic development, widespread poverty, water scarcity, low access to electricity, low efficiency of water use, rapid population growth and increasing demand for water (Georgakakos, 2007). The basin countries have developed extensive plans for water resource developments to contribute to the needs for energy and food production in the region (Block, 2007; Goor et al., 2010, 2011; Guariso and Whittington, 1987; Jeuland, 2010; Whittington et al., 2005).

Water resources related issues in the Eastern Nile are complex (Belachew et al., 2015). The river flow regime is characterized by large seasonal and inter-annual variability (Goor et al., 2010). On the basis of source and use of water, the basin countries can be divided into two groups: the upstream countries of Ethiopia and South Sudan, which are net producers of Nile water and use relatively small amounts, and the downstream countries of Sudan and Egypt, which are net consumers of Nile water and use relatively large amounts of water. Most of the existing water resources developments in the Eastern Nile basin have taken place in the downstream part of the basin. The emerging upstream water resources developments would affect the existing downstream dams, leading to both positive and negative externalities.

The absence of formal mechanisms for transboundary collaboration increases the challenges and the chance of conflict between upstream and downstream riparian nations. The Nile basin countries have launched the Nile Basin Initiative (NBI) to develop the Nile Basin water resources in a sustainable and equitable way. However, the countries have in the meantime developed their own plans for water resources management unilaterally (Cascão, 2009; McCartney and Menker Girma, 2012). "Unilateral" or “un-integrated” is used here to refer to non-cooperative management of the river system and contrasts with integrated transboundary management.

Therefore, specialized tools for analyzing water resources development and addressing the related technical, environmental, social and economic issues are critically needed. Integrated assessment of the impacts of new dam developments in a regional context and sharing data and information is important to support decision making for evidence-based policies that are likely to enhance the collaboration between basin countries and prevent conflicts.

Water resources system planning and analysis methods are extensively reported in the literature (Fayaed et al., 2013; Labadie, 2004; Loucks et al., 1981; Rani and Moreira, 2010; Wurbs, 1993; Yeh, 1985). Conceptually, these methods are divided into three approaches: simulation methods, optimization methods, and hybrid combinations of both (Kim and Wurbs, 2011). Optimization methods are used for screening a large number of alternatives to generate a small number of feasible ones. Simulation methods are used for both examining system performance under certain conditions, and screening a limited number of alternatives by means of scenarios (Kim and Wurbs, 2011). Simulation methods aim to provide detailed and realistic representations of the physical, environmental, economical, and social characteristics of the system (Nandalal and Simonovic, 2003). They can give insights into the dynamics and structure of the system. Therefore, simulation models are popular among reservoir managers and utilities that are responsible for water resources management.

In the Nile basin, a number of simulation models have been developed to study various aspects of water resource developments. Several studies focused on the operation of a particular dam (Abreha, 2010; Hurst et al., 1966; Mohamed, 1990; Wassie, 2008). Some studies concentrated on the Blue Nile basin highlighting the climate change impacts on the planned dams during both filling (Block, 2007; King and Block, 2014; Zhang et al., 2015, 2016) and operation stages (Jeuland and Whittington, 2014; McCartney et al., 2012; McCartney and Menker Girma, 2012; Wondimagegnehu and Tadele, 2015). Wheeler et al (2016) investigated 224 filling strategies of the Grand Ethiopian Renaissance Dam (GERD) and reoperation of existing dams in Sudan and Egypt assuming different levels of coordinated operation with GERD. The impact of filling the planned Blue Nile cascade of dams on irrigation and hydropower downstream was investigated by Mulat and Moges (2014b), who also assessed the impact of GERD on the performance of the Aswan High Dam in Egypt (Mulat and

Moges, 2014a). The Nile basin was investigated as one unit in the Nile valley plan; the study focused on the hydraulic aspects to identify the best controlling dam system (Morrice and Allan, 1958). The Nile River basin Decision Support Tool (DST) was developed to assess the benefits and tradeoffs associated with different water development and management options in the Nile basin (Andjelic, 2009; Georgakakos, 2006). Blackmore and Whittington (2008) used DST with a 64-year historical hydrological sequence to assess the impact of some unilateral developments on the Eastern Nile under current conditions. The Nile Basin Initiative developed a decision support system using MIKE Basin for simulation together with five different optimization algorithms (NBI, 2013). Recently, several simulation models (Riverware, RIBASIM, MIKE Basin and HEC-ResSim) have been developed for the Eastern Nile basin under the Eastern Nile Planning Model project (ENPM), managed by the Eastern Nile Technical Regional Office (ENTRO). The models have been developed to strengthen the knowledge and modelling capacities of institutions in the region for addressing and supporting water resources development and management.

Most studies have modelled the Nile basin to address (specific) water resources related issues and associated implications, e.g., filling of planned dams, optimization of reservoir operation, impacts of climate change, etc. They have used different approaches (simulation, optimization, economic analysis, etc.), for varying topologies of the system, using different lengths of the boundary conditions. Although those studies gave good insights of the system and expected impacts, still the picture is not fully understood for different topologies and probabilities of river inflows. Therefore, studying water resources development options in a regional context is still important to quantify the impacts both at regional and at country level. Quantifying benefits of managing the reservoirs system as one single unit, i.e., regardless of the political boundaries, is a prerequisite to quantifying potential benefits of cooperative management, which may stimulate cooperation among the riparian states.

The aim of this study is to quantitatively analyse the Eastern Nile water resources development options, based on the recent plans for dam and irrigation development (2012), considering different management options. Four indicators are used: hydro-energy generation, irrigation supply reliability, evaporation losses induced by the reservoirs and the change of the basin's flow regime. A river basin simulation model for the Eastern Nile basin has been developed using RIBASIM. The analysis has been carried out through developing different scenarios for dam and irrigation developments, hydropower demands and system management options. The scenarios have been run on a monthly time step for 103 years (1900 to 2002). The historical stream flows of the Nile basin have shown to be relatively stationary, though some trends are evident at localized tributaries (Taye et al., 2015). Taye and Willems (2012) demonstrated the occurrence of a multi-decadal pattern in the Blue Nile river. Therefore, use of a short data set of stream flow might be not sufficient. Unlike most previous deterministic and simulation-based studies, a long series of historical stream flow data have been used in the model to capture the temporal variability of flows. In addition, the use of RIBASIM simulation model facilitates a manual optimization of the scenarios through varying the sources of supply of the water users.

Existing and proposed water resource projects

The Eastern Nile countries utilize their rivers mainly for irrigation, hydropower, domestic and industrial water use, among which irrigation represents the largest portion of consumptive water demand (Mulat and Moges, 2014b; Timmerman, 2005). The hydro system of the Eastern Nile consists of ten major hydraulic dams that are currently operational (**Figure 1**).

In Ethiopia, the Tana-Beles Scheme on the Blue Nile consists of an artificial link between Lake Tana and the Beles River to generate hydroelectricity (460 MW) and planned irrigation development of around 150,000 ha. Tekeze dam (9.3×10^9 m^3) on the Tekeze-Atbara has an installed capacity of 300 MW (Goor et al., 2010); there is not yet large irrigation projects in the Tekeze-Atbara river basin. A small scale irrigation project (1,800 ha) is irrigated from a dam constructed in the Angereb river, a tributary of the Tekeze-Atbara.

In Sudan, there are two major dams on the Blue Nile, Roseires (heightened by 10 meters in 2012, to double its storage capacity) and Sennar dams. The main objective of those dams is to regulate the seasonal flow of the Blue Nile waters for irrigation of more than one million ha of crops distributed over three irrigation schemes (Gezira, Rahad, Suki). Their electricity production is relatively small, attributed to the limited available head, 280 MW and 16 MW at Roseires and Sennar respectively. On the Atbara River, the Khashm Elgirba dam has a relatively small hydropower capacity (10.6 MW). All abovementioned dams in Sudan face severe siltation problems. The siltation problem at Khashm Elgirba dam is managed by means of flushing. Reservoir sedimentation at Roseires and Sennar dams are managed by keeping minimum water levels during the flood season, and only starting to fill after the peak load of sediment has passed. Jebel Aulia dam, located on the While Nile near the confluence with the Blue Nile, provides water for irrigation schemes around the reservoir estimated at 275,000 ha. At the Main Nile, close to the 4th cataract, Merowe dam (12.5×10^9 m^3) has an installed generation capacity of 1250 MW and can potentially irrigate 380,000 ha.

In Egypt, there are five run-of- river dams and one major dam, the Aswan High Dam (AHD) being the major dam of the basin. The main objectives of AHD are to produce energy, to supply irrigation water, to regulate the flows to protect downstream against flooding and improve downstream navigation. The Old Aswan dam (OAD), located downstream of the AHD, is operated as a run-of-river hydropower plant. It is mainly used for hydropower production and to regulate the daily outflows from AHD (Goor et al., 2010). The Esna run-off- river plant located downstream OAD is operated for hydro-power generation. The last three barrages, Assyut, Delta and Naga Hammadi divert Nile water to collectively irrigate 1.315 million ha. However, the simulation model built in this study ends at AHD, and considers Egypt downstream annual demand as fixed at 55.5 bcm.

Many new reservoirs and irrigation projects have been proposed in the Eastern Nile Basin, particularly in the Ethiopian part of the basin (**Table 5-Appendix**). The potential hydropower of the Blue Nile is estimated at 13,000 MW (Mulat and Moges, 2014b). Perhaps not all proposed dams across the Ethiopian Blue Nile (Abay) are likely to be constructed in the near future, as some sites are mutually incompatible. Those reservoirs on the stem of main tributaries with high generation capacities and those irrigation projects with large demands for water are considered in this study (**Figure 1**). Six potential dam sites have been identified along the Main Nile in Sudan with a total potential energy generation capacity of 1,600 MW (Verhoeven, 2011). The potential of new irrigation in Sudan is estimated at 590,000 ha withdrawing water from the Blue Nile, 90,000 ha from the White Nile and 285,000 ha from the Atbara (ENTRO, 2007; Van der Krogt and Ogink, 2013).

It should be noted that all current and plans for new irrigation development in Sudan on the Eastern Nile have water requirements that would exceed its agreed allocation with Egypt. Ethiopa's planned irrigation developments would further increase the pressure on water resources, in particular for Egypt. It is therefore unlikely that all planned irrigation developments would materialise.

Materials and methods

Model and data

The RIBASIM modelling software is used to model and analyze the Eastern Nile system by means of different scenarios (**Table 1**). The scenarios have been selected to represent the base case (S0), and then different dams' development in both Ethiopia and Sudan, as well as irrigation demands in both countries. RIBASIM simulates the performance of a system using hydrologic time series and allocation rules (Abreha, 2010; Van der Krogt, 2008; Van der Krogt and Boccalon, 2013; Verhaeghe et al., 1988). The model uses nodes and links to represent the river system components. The model links hydrologic inputs at various locations in the basin with water users. Water allocation can be simulated by setting source priority list for each water user. To allocate water among multiple competing demands, each water user has a specified water allocation priority. The monthly available water is allocated to the users by priority, first priority 1, next priority 2, etc. till the last specified priority. If users have the same water allocation priority then the upstream water users get the water before downstream users. As an example of the priority system of RIBASIM, water supply for the Gezira Scheme (abstracting upstream Sennar dam), is first supplied from Sennar dam, if not enough then from Roseires dam

The Eastern Nile system considered here is up to the Aswan High Dam (AHD). Data of the Eastern Nile basin has been collected from various sources, including: the Ministry of Water Resources and Electricity (MWRE) - Sudan, Nile Water Master Plan (MOI, 1979), Roseires Heightening Report (McLellan, 1987), periodical reports published by the Ministry of Agriculture - Sudan (Ministry of Agriculture, 2013) and data of the Eastern Nile Planning model (ENPM) from ENTRO (Van der Krogt and Ogink, 2013)

To model the irrigation schemes of the basin, a fixed irrigation node was used. It requires data in the form of irrigated area (ha) and net average monthly demand (mm/d). In reality, the demands for most irrigation schemes (except those for perennial crops such as sugarcane) vary annually, as the cultivated area may be adjusted to fit the expected inflow. In this study, the demand (per ha) was assumed to remain constant over the years. The total potential area is used and assumed to be equally distributed between the different crops. Effective rainfall was considered negligible and ignored when determining irrigation demand. The potential areas of existing and planned irrigation projects in Sudan and Ethiopia have been taken from the Nile Water Master Plan (MOI, 1979) and from ENPM. Crop water requirement (ET_{crop}) (mm/d) of the potential and existing irrigation schemes have been calculated from FAO data including crop factors (K_c) and the Penman-Monteith reference evapo-transpiration (ET_o) (mm/d). The total irrigation demand of Sudan in the base scenario thus amounts to 18.5 x 10^9 m^3/year. The annual irrigation demand in Egypt was assumed to be equal to Egypt's water demand in the 1959 agreement between Sudan and Egypt (55.5 x 10^9 m^3/year). The monthly demand pattern is taken from Oven-Thompson et al. (1982), the maximum monthly demand occurring during June and July. A similar assumption has been used by Goor et al. (2010) and Van der Krogt and Ogink (2013).

In RIBASIM, variable flow nodes are used to represent the natural water flowing through the river system. Water balance calculations are applied using a spreadsheet to generate the monthly time series of incremental natural flow of tributaries (represented by variable flow nodes) between gauge stations (record nodes). The hydrologic time series (103 years of monthly data set from January 1900 to December 2002) of the recorded (measured) station, rainfall and evaporation data at dam sites were supplied by ENTRO and as used in the ENPM. The model uses rainfall and evaporation data for the water balance calculations of the reservoirs. Effective rainfall data (1960-2000) are based on ERA40 gridded daily rainfall from the European Centre for Medium range Weather Forecast (ECMWF). Potential evaporation rates data of Egypt, Ethiopia and Sudan are based on the FAO database (Van der Krogt and Ogink, 2013). More details on data processing, generation and validation are available in Van der Krogt and Ogink (2013).

Model data of reservoirs in RIBASIM are the physical characteristics of the reservoir, main gate and hydropower plant characteristics (turbine capacity, efficiency, tail water level and losses), firm energy (demand and allocation priority) and operating rules. The operating rules are defined by identifying the flood control, target and firm storage levels and applying two hedging (reduction) methods for water releases from reservoir when water level drops below the specified firm storage level. Here, storage-based hedging was used. Storage-based hedging is supply based operation where reservoir releases are determined by the available storage and upstream inflow rather than the demand of downstream water users. Storage-based hedging requires defining distinct zones below firm storage and for each the percentage of the target release (full demand of all downstream users) that will be released for each zone (Table S1-Online supplemental data); the lower zone from which water is released, the larger the reduction of the target release (Van der Krogt and Ogink, 2013). Operating rules of the planned dams are not known; we have chosen to simulate dam releases using the storage-based hedging method.

Simulation model

Two Eastern Nile models have been developed, one based on integrated transboundary operation of all dams in the basin, and one where countries operate the dams unilaterally. This can be modelled in RIBASIM by settings in the source priority list. The list can either be empty or not**.** The default source priority list generated by RIBASIM model for each water user in a network includes all upstream supply sources that a user can receive water from. Water users with an empty source priority list cannot claim water from upstream sources to satisfy their demand and can only use the water available at their location, including uncontrolled flows (natural flows from variable flow nodes) and water released from upstream sources without considering downstream demand. A more detailed description of the water allocation procedure of RIBASIM is given in Van der Krogt and Boccalon (2013). For modelling integrated transboundary management of the Eastern Nile system, the source priority list for each water user contains those upstream supply sources that can be used to satisfy the demand having the same logic of network links. In the unilateral scenario, the source priority list of the dams located near a border, i.e. Roseires, Khashm Elgirba (which is replaced by Settit dam once it gets online) and AHD were set as empty. The source priorities of the rest of the dams were not empty as there still is coordinated dam operation within each country; however, users cannot claim their demand from upstream sources beyond the border dam in their country.

Priorities of water users do not change with time but do with space depending mostly on the purpose of the supply infrastructure or dam. If the dam is constructed to be operated for hydropower generation only, such as the upstream Blue Nile dams in Ethiopia, generating firm demand will take priority over downstream demands. In case there is sufficient water to satisfy both firm energy and downstream water demands, such a reservoir releases water to fulfil all demands. In case water is insufficient, power generation takes priority over downstream demands and therefore the amount of water released for downstream demands will be reduced by the specified hedging rules.

If a dam is multipurpose for both hydropower and downstream irrigation, such as all existing dams, the priority will depend on the actual operation. For example, Roseires and Sennar on the Blue Nile of Sudan are operated for both hydropower and irrigation with the priority given to the irrigation demands of Sennar, Gezira and Managil schemes. For new dams with both hydropower and downstream irrigation dams such as Hummera and Settit on the Tekeze-Atbara River, hydropower and downstream irrigation were assumed to have the same priority.

The simulation cases within each model were compared to assess the implication of planned new dams and irrigation demands (Objective 1). The two models were also compared to assess the value of integrated and unilateral operation for the dams in the entire basin and all countries (Objective 2).

Simulation cases

Apart from the baseline (S0), 12 scenarios were developed from the combination of (1) three dam development options (S1, S2 and S3); (2) two irrigation demand conditions; before any potential irrigation project realization (S10, S20, and S30), and after (S11, S21, and S31); and (3) two system management conditions: integrated transboundary management with cases denoted as Sxx0, and unilateral management, with cases denoted as Sxx1 (**Table 1**). Development of irrigation projects varies with scenarios because they are associated with the development of some dams that will be operated for hydropower generation and irrigation. The additional development of irrigation in S31 is attributed to development of irrigation schemes in the White Nile River; however there are no planned dams on the White Nile. Operations of GERD are based on the uniform firm energy generation that can be satisfied 95% of the simulated time horizon. According to our simulations, the firm energy demand that GERD can satisfy is equivalent to 1,725 MW of continuous generation, while total energy generation reaches 15.1 TWh/year, which is in line with Bates et al. (2012).

The baseline scenario (S0) considers the system as in the year 2011 before the heightening of Roseires reservoir. Data of the actual abstractions (e.g., for Gezira Scheme) are used to calculate the cropped areas A (ha) for model calibration and validation. In actual operation, the cropping areas of operational irrigation schemes in Sudan vary annually, based on the predicted inflow to Roseires dam; this is particularly true for the winter crops in central and northern Sudan. The average abstraction of irrigation projects per each month is therefore used to estimate the cropped area using given the monthly crop water requirement. The potential areas of irrigation projects are then used in the base and other scenarios.

The first scenario of dams' development (S10) represents the system after GERD, and Roseires Heightening, with no additional irrigation development. The first scenario with irrigation developments (S11) includes additional irrigated agriculture in Ethiopia (total demand 1.32 x 10^6 m^3/yr), and in Sudan (total demand 25.2 instead of 18.5 x 10^6 m^3/yr). Therefore, the impact of GERD on the current system can be assessed by comparing scenarios S1x against S0. E.g., comparing S11 to S0 will indicate the impact of GERD on agriculture expansion of Sudan and also the impact of agriculture expansion on hydropower generation of the three countries.

The second scenario (S2) considers all dam developments upstream in Ethiopia at the Blue Nile and Tekeze-Atbara rivers (Table 1), represented as S20 and S21 for no, and complete agriculture expansion, respectively. Therefore, comparing S2x to S0 will reveal the impact of upper basin full development on the hydropower and irrigation in the Eastern Nile system.

The third scenario (S3) represents full development of the basin dam and irrigation projects. S3 differ from S2 in that the Main Nile dams (S30) and irrigation projects (S31) in Sudan get online. Comparing S3 to S2 will indicate the impact of upstream and downstream water resources development on the basin's countries.

In the integrated transboundary management scenarios, all water users are connected to one or more upstream sources depending on the network links. In case of two parallel reaches, water user located downstream the confluence will have two sources, the order of these sources depends on how much water each reach have. The most downstream demands are connected to the most upstream sources through the intermediate sources. For example, AHD demands can be fulfilled from its upstream source Dal dam, and Dal dam's demand from Kajabar dam, until the demand reaches Roseires and then GERD. When the system is managed unilaterally, the source priority list of AHD being empty, the demand of AHD cannot be fulfilled from Dal; rather, AHD receives only what Dal dam releases according to its own demand to produce energy (there is no irrigation demand between Dal and AHD). In other words, dams in each country are operated independently for the unilateral scenario, but could be dependently operated within the country.

Model assumptions

In this study, all dam developments are assumed online and at operational stage; the transient stage (filling) and their short-term impacts have not been considered. In the initial condition of simulation, water levels of all reservoirs in the system are assumed full. The existing and proposed developments in Baro-Akobo-Sobat sub-basin have negligible effects on the system compared to the proposed large reservoirs in the other sub-basins and were therefore omitted. The potential irrigation projects of the upper basin withdrawing water from the Blue Nile and Tekeze-Atbara rivers are estimated at 0.2 x 10^6 ha (Goor et al., 2010; Van der Krogt and Ogink, 2013). Domestic and industrial demands are negligible in the Eastern Nile basin compared to irrigation demand, therefore they were not considered. We further assume that the historical time series of 1900 to 2002 is representative of future discharges. This neglects any climate change effects, which is beyond the scope of this paper. Usable storage of the reservoirs was assumed to be constant in future, despite the fact that due to the siltation these storages are likely to reduce over time.

Model calibration and validation

For model calibration, the monthly irrigation demand was assumed to be identical to the measured abstractions of all irrigation projects during the year July 1970 - June 1971. The simulated abstractions of irrigation schemes and reservoir releases were compared to the measured ones.

Hedging rules based on storage, target levels of the operation rule and the power plant factor were used as adjustable parameters for calibration. The storage between firm level and dead storage level was divided into zones, water allocation at those zones were considered as a percentage of target releases and tested for different percentages between 100% and 20% resulting in significant improvement in the model output (Table S1-Online supplemental data). The model was run for different target levels ranging between full reservoir level and firm level (or minimum operation) to adjust reservoir releases and supply of irrigation demand. As the power plant factor of existing dams of 90 % gave the best results, this factor was used. The results showed that the simulated and measured downstream releases and water levels of Roseires and Sennar dams are more or less the same. Also, the demand (measured) and supply (simulated) of irrigation projects are equal**,** indicating that the model performs well.

To reduce errors during model verification that could result from the change of available storage due to siltation, and thus resulting in differences between simulated and measured values, the physical characteristics of Level-Area-Volume relations of reservoirs derived from the available bathometric survey were adjusted according to the years of calibration and validation. Additional calibration data and results are provided in the online supplemental data.

The model was validated using demand data for three years (July to June); 1977-1978, 1984-1985, and 1988-1989 representing normal, dry and wet years, respectively. For each hydrologic condition year, the model was run for the entire period (1900-2002) with the demand fixed at the actual abstraction of the year. The identification of the wet, dry and normal years was based on a comparison between the average monthly flow at Border (Eldiem) station 1965-2012 and the average monthly flow of the three years.

Results and Analysis

Although results have been analyzed for the 12 scenarios, the paper focuses on the results of the scenarios that include GERD development under both integrated transboundary and unilateral management, and with and without agriculture expansion. Other major results will be mentioned where relevant. However, the full set of results is available as online supplementary material. We start with presenting the validation results, then follow hydropower generation, irrigation development, and their impacts on evaporation losses from reservoirs and on the hydrographs.

Model validation

Figure 2 displays the simulated and measured flow at the Blue Nile, and the Main Nile for a dry, normal and wet year. The results showed slight differences between simulated and measured flow during the wet season (July-October) downstream of dams in the Blue Nile River. These differences are in part due to the filling and operation of Roseires, Sennar and Kashm El Girba for sediment management. The time step used for filling (daily for 45 days) of Roseires and Sennar reservoirs differs from that used in the model (monthly). For reservoir sedimentation management, all gates are opened to release the coming inflow to pass the peak of sediment (and not to meet the downstream demands). The results also showed that simulated flow at Dongola station at the Main Nile is less than the measured flow, probably because of small flows from unmeasured tributaries of the Main Nile or to underestimated abstraction from the Main Nile.

The results of supplies and demands of Gezira, Managil and New Halfa irrigation projects during the three years showed that all the demands (the measured abstraction) are met, indicating the capability of the model to simulate the demand.

The model accuracy was tested by calculating three model performance evaluation criteria: Root Mean Square Error (RMSE), Nash-Sutcliffe coefficient (E) and the correlation (r^2) for the simulated and measured stream flow at previously mentioned key stations. The results (**Table 2**) showed reasonable RMSE values (< half of measured flow standard deviation, according to Moriasi et al. (2007)) except at Khartoum, Tamanyat and Dongola station during the dry year. However; the correlation between simulated and measured flows at the two sites are very high (> 0.9) and Nash-Sutcliffe coefficients are reasonable (>0.5).

Hydropower generation

Integrated transboundary management

Figure 3 shows box-plots of the annual generated hydro-energy of the three countries for the base scenario (S0), and with GERD dam development (S1xx), including with/without irrigation developments (S10x, S11x), and integrated transboundary/unilateral management scenarios (S1x0, S1x1). Hydro-energy generation in Ethiopia would boost by 1,500% after GERD gets operational (S100). Sudan hydro-generation showed an increase of 17% (S100) compared to the present generation. Hydro-energy generation at AHD in Egypt would slightly decrease by 1% after GERD (S100). Despite the variation in the methodology and the downstream boundaries of the studies, the results have a similar order of magnitude as those reported by Arjoon et al. (2014) after GERD gets online; they found that energy generation would increase by 1,114% in Ethiopia, by 15% in Sudan and by 2% in Egypt. The fact that we find a slight decrease for Egypt can be explained by the possibility of operating AHD under relatively low water head level (Guariso and Whittington, 1987)**.**

Figure 3 also displays the impact of irrigation developments on hydro-energy generation, where a general trend of reduction of energy-generation of the countries is shown compared to the without irrigation development scenarios. This is expected because of the consumptive nature of irrigation water. Energy generation in Sudan would reduce by 6.5% (S110), because most potential irrigation lies between Roseires and Sennar which both give priority to irrigation. The reduction in the case of AHD would reach 13% after upstream irrigation development (S110). The four scenarios for Ethiopia (S100, S110, S101, S111) show no big difference. In other words hydropower generation from the GERD is not affected by irrigation development – because the latter mainly occurs downstream. The overall basin hydropower generation is boosted by the GERD from 20,000 to over 35,000 GWhr. This is not influenced by either integrated transboundary or unilateral management, though slightly reduced by irrigation development.

The results of considering additional hydropower dams (S2 and S3) are presented in Table 3. Although hydropower generation increases substantially by the new dams, all scenarios show no significant difference between integrated transboundary and unilateral management except for S31. In the S31 scenario, Ethiopia hydropower generation reduces from 36,035 to 23,604 GWhr/yr if the system operated in an integrated fashion, while for Sudan (S310 *vs.* S311) hydropower generation reduces from 15,001 to 13,129 GWhr/yr. Both reductions are attributed to the fact that in the integrated case of system management, Ethiopian dams are operated considering the demand of the downstream countries, which has much increased because of the development of irrigation projects in Sudan; yet these demands would not be considered in the unilateral case. Similarly, the reduction of Sudan hydropower generation is because downstream demand of Egypt would be considered when operating the dams in Sudan, in addition to the increased demand resulting from the development of irrigation projects upstream the new hydropower dams of the Main Nile. Hydro-energy generation of Egypt would not much be affected by GERD, with or without integrated transboundary management. This result is similar to that found by Arjoon et al. (2014), who show a negligible loss or gain in Egyptian hydropower generation resulting from unilateral management of the reservoir system (GERD). In the unilateral management scenario Egypt would nevertheless benefit from water released from the Merowe dam at the Main Nile for energy production, as this scenario (S111) does not yet consider irrigation expansion immediately downstream of Merowe.

Irrigation development

Table 4 summarizes the monthly supply reliability (average monthly supply to demand ratio) of existing and potential irrigation projects. The table shows a decrease in the supply-demand ratio of existing irrigation in Egypt by 1% after the GERD (S0 vs. S100 and S101), indicating no differences between integrated transboundary and unilateral management of the system.

The reliability of irrigation supply to Sudan is practically not influenced by the GERD, but reduces by about 8% when upstream development and new irrigation expansion materialized. Integrated transboundary management does not change results except for the last scenario S31, whereby reliability reduces from 90 to 80% from integrated to unilateral management.

For Ethiopia, reliability of irrigation supply significantly differs for integrated transboundary and unilateral management (S11, S21, and S31).

The analysis of the probability of non-exceedance of irrigation supply of existing and potential projects in Sudan (**Figure 4**) reveals that the supply reliability of the existing irrigation in Sudan has a chance of 0.99 to be higher than 80%, in all scenarios and under both integrated transboundary and unilateral management of the system, except in the case of full basin development and managed unilaterally; the chance would reduce to 0.75 (S301) (Figure S8 - online supplementary data). A supply reliability of 80% represents an acceptable assurance of supply for irrigation schemes, given the possibility of practicing deficit irrigation practice (Steduto et al., 2012). Unilateral management of the system would not affect the chance of achieving a supply reliability of 80% for existing and potential irrigation with dams development except when all dams get online (S311) when it would reach 67% (Figure S8 - online supplementary data). The supply reliability of irrigation projects in Ethiopia (not shown here) would be 1.00 for the scenario of GERD development under both integrated transboundary (S110) and unilateral management (S111),

Net evaporation loss from reservoirs

Figure 5 displays the average annual net evaporation from reservoirs of the countries at each dam developments scenario, with and without irrigation development, under integrated transboundary and unilateral management of the system.

In case of integrated management and without irrigation development, evaporation losses from Ethiopian reservoirs would increase from 0.20 x 10^9 m^3/yr (S0) to 1.8 x 10^9 m^3/yr after GERD is operational (S100). The average evaporation loss from Sudan reservoirs showed an increase to 6.2 x 10^9 m^3/yr after GERD. Net evaporation from AHD would decrease from 13.3 x 10^9 m^3/yr (S0) to 12.1 x 10^9 m^3/yr after GERD (S100) gets operational, due to the reduced storage of AHD. Results in **Figure 5** indicate that, compared to the scenarios without irrigation development, the development of irrigation projects would induce small reductions of the net evaporation in Ethiopia and Sudan, and large reductions from Egypt's main reservoir, which is expected, because less water would be flowing into Egypt, resulting in AHD water levels to drop and with it the water surface area.

Taking a basin level perspective, the change of net evaporation from all dams would be insignificant after dam development in Ethiopia, while evaporation would increase with developments of the Main Nile dams. Unilateral system operation would have insignificant impact on net evaporation compared to that resulting from operating the system in an integrated manner, until the development of the Main Nile dams, when net evaporation would increase as indicated in **Figure 5** due to the high evaporation losses in the Sudanese reservoirs on the Main Nile.

Stream flow hydrographs

The average monthly inflows of the Main and the Blue Nile at the Egypt -Sudan (AHD) and Sudan-Ethiopia (Border or Eldiem) border are shown in **Figure 6**. The results show significant impacts of basin developments on the flow regime, represented by a reduction of the inflow during the wet season (July to September) and an increase during the dry season (October to April). In case of no irrigation projects are developed and the system is operated in an integrated transboundary manner, the average monthly inflow at AHD would range between a minimum and a maximum of 1,420-4,135 m^3/s (average 2,186 m^3/s) after GERD (S100) compared to the base scenario (S0) (1,055-7,071 m^3/s with 2,733 m^3/s average). Development of irrigation projects would reduce flows to 1,239-3,570 m^3/s (average 1,915 m^3/s) after GERD (S110). The results are similar to the findings of Goor et al. (2010) and Arjoon et al. (2014) who also observed an augmentation of low flows and a reduction of high flows with GERD development. In case of unilateral system management, the variation would follow the same pattern, with a slight increase of the flow compared to those resulting from integrated system management.

Inflows from Ethiopia at Border (Eldiem) would reduce in variability due to upstream dam developments. If the system is operated in an integrated manner, the minimum and the maximum average monthly inflow would be 1,311-2,808 m^3/s after GERD gets operational (S100), compared to the base scenario (S0) (134-5,447 m^3/s). Unilateral system management would not significantly change these flows at Border (Eldiem).

Figure 7 displays the probability of non-exceedance of the annual inflow at AHD and Border (Eldiem). According to the 1959 Nile water agreement between Sudan and Egypt, the inflow to AHD was supposed to be 65.5 x 10^9 m^3/yr, accounting for both Egypt's share (55.5 x 10^9 m^3/yr) and the additional evaporation losses due to the AHD that were then anticipated (10 x 10^9 m^3/yr. **Figure 7** shows that the probability that Egyptian's claim is not met would increase from 23% in the base scenario (S0) to 42% if GERD (S100) would be in place and the system would be managed in an integrated manner. The modelled probability of non-exceedance is relatively high in the base scenario compared to the generally accepted observations that AHD has so far mostly received annual inflow greater than the claimed share of Egypt. The high modelled value of probability of non-exceedance is because the model assumes that all irrigation schemes considered in the base scenario have been developed to their potential area, which is not yet the case.

The annual flow at the Sudanese-Ethiopian border (Border or Eldiem) shown in **Figure 7** demonstrates that the probability of getting inflows greater than 48 x 10^9 m^3/yr is greater than 50% in the base case. The probability of getting the same inflow would remain the same in all dam development scenarios (S100, S200 and S300). When the system is operated unilaterally, the probability would not significantly change compared to the integrated operation of the system.

Conclusion

A simulation model for the Eastern Nile basin was developed with which 12 scenarios (plus base scenario) were evaluated to assess the impact of dams and irrigation development in the basin on four performance indicators: hydropower generation, irrigation supply reliability, evaporation losses from reservoirs and change of the flow regime. The analysis focused also on the effect of system management, i.e., an integrated transboundary and unilateral management scenarios. The results of the simulation model indicate that dams and irrigation developments would generally have significant impact on the performance indicators.

When the system is operated in an integrated manner, the new dam developments would boost the hydropower generation in Ethiopia. The hydro-generation would increase in Sudan and slightly decrease in Egypt. Development of new irrigation projects would, however, reduce the power potential of the three countries but by less than 15%. Power generation losses at AHD are very small due to dam developments in Ethiopia; however power generation would be significantly reduced with the planned expansion of upstream irrigation.

Development of GERD in Ethiopia would (slightly) increase the supply reliability of existing irrigation projects in Sudan, but will slightly reduce if additional irrigation is developed. The supply reliability of existing and potential irrigation projects would generally decrease with dam development, because most new large dams are operated for hydropower generation. The supply-demand ratio of Sudanese irrigation projects would be reduced with the development of new irrigation projects under both integrated transboundary and unilateral system management, with greater reductions in the latter. Full development of all planned dams in the basin would cause greater reductions in the supply-demand ratio for irrigation.

Development of dams would also significantly affect the total net evaporation losses from reservoirs compared to the base scenario. While the basin-wide evaporation losses from reservoirs showed insignificant changes with the development of Ethiopian dams, the losses would increase with the development of the Main Nile dams in Sudan.

The flow regime would be significantly influenced by dam and irrigation developments. Flows in the wet season would decrease while they would increase during the dry season. The results also reveal that the probability of Egypt not receiving its share to Nile water (inflows into AHD of 65.5 x 10^9 m^3/yr) would increase by the development of some hydropower dams in the upper basins. Managing the system unilaterally showed that, compared to integrated system management, the generated power would increase in Ethiopia, and decrease in Sudan and Egypt by dam development in Ethiopia, even without any further irrigation development. Power generation in Sudan and Egypt would, however, increase when the Main Nile dams get operational. Development of potential irrigation would generally decrease the generated hydropower. Supply reliability of existing irrigation projects would not be affected by dam development until the development of the Main Nile dams in Sudan, when the reliability would reduce.

Most of the new large dams in the Eastern Nile are designed for hydropower generation. Results have therefore shown limited influence of dam developments and system management options on the inflow to AHD and thus hydropower-generation and downstream releases. The Main Nile reservoirs in Sudan are planned for hydro-generation only so far. This explains the increase of AHD hydro-generation by 10% in the unilateral compared to the integrated management scenario and by development of the Main Nile dams.

In conclusion, the model provides quantitative information to understand the consequences of the available plans of dam development and agricultural expansion in the basin. Planning and managing the entire Eastern Nile basin in an integrated manner achieves benefits for all countries and reduces losses compared to the case of unilateral management, including evaporation losses and a reduction in supply reliability, provided that excessive irrigation development beyond sustainable levels of water availability is avoided. In addition, one may assume that unilateral management might also increase political tensions, which may lead to other types of losses, including economic.

The analysis does not include the influence of the high sediment load of some rivers (i.e. Blue Nile, Tekeze-Atbara) that significantly affects the usable storage of existing and future reservoirs. Further analysis of the silting up of reservoirs is required to better understand how dams affect and are affected by the sediment problem. In the Eastern Nile, sediment loads in rivers are a transboundary issue.

Appendix

Acknowledgements

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Online Supplemental Data

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Table 1 Description of the scenarios.

Developments	**Country**	**S0 (Base)**	**S1 (S10), (S11)**	**S2 (S20), (S21)**	**S3 (S30), (S31)**
Infrastructures (reservoirs)	Ethiopia	Tiss Abbay I, II	S0	S1	S2
		Tana Beles TK5 Atbr_smalIrr_Ir(E) - Angereb River	GERD	Mendaya BekoAbo Karadobi Humera Metama	
	Sudan	Roseires Sennar Kashm El Girba Jebel Aulia Merowe	S0 Roseires-Heightened	S1 Settit	S2 Dal Sheriq Kajabar Sbloga
	Egypt	AHD	S0	S0	S0
	Total installed capacity (GW)	**3.93**	**9.64**	**14.31**	**15.34**
Annual Irrigation water demand upstream of AHD (10^9 m^3)	Ethiopia	0	S10 : 0 S11 : 1.32	S20 : 0 S21 : 1.96	S30 : 0 S31 : 1.96
	Sudan	18.5	S10 : 18.5 S11: 25.2	S20 : 18.5 S21 :28.5	S30 : 18.5 S31 :30.8
Annual water demand downstream of AHD* (10^9 m^3)	Egypt	55.5	55.5	55.5	55.5
	Total (10^9 m^3)	74	82.02	85.96	88.26

***** The annual irrigation demand in Egypt is assumed to be equal to Egypt's water demand in the 1959 agreement.

Table 2 Results of three measures for the model performance evaluation

	Dry year (Jul1984-June 1985)			Normal Year (July 1977-June 1978)			Wet Year (July 1988- June 1989)		
	RMSE (m^3/sec)	Nash-Sutcliff coefficient (E)	Correlation (r^2)	RMSE (m^3/sec)	Nash-Sutcliff coefficient (E)	Correlation (r^2)	RMSE (m^3/sec)	Nash-Sutcliff coefficient (E)	Correlation (r^2)
Roseires	130 (< 1/2 CV)	0.93	0.97	205 (< 1/2 CV)	0.99	0.99	544 (< 1/2 CV)	0.97	0.98
Sennar	185 (< 1/2 CV)	0.92	0.97	294 (< 1/2 CV)	0.98	0.99	673 (< 1/2 CV)	0.95	0.96
Khartoum	475 (> 1/2 CV)	0.71	0.97	612 (< 1/2 CV)	0.93	0.96	1215 (< 1/2 CV)	0.86	0.89
Atb_K3	78 (< 1/2 CV)	0.99	0.92	147 (< 1/2 CV)	0.96	0.97	140 (< 1/2 CV)	0.98	0.99
Dongola	633 (> 1/2 CV)	0.81	0.91	1098 (< 1/2 CV)	0.92	0.98	1465 (< 1/2 CV)	0.91	0.91
Tamanyat	*278* *(> 1/2 CV)*	0.89	0.96	455 (< 1/2 CV)	0.98	0.97	1020 (< 1/2 CV)	0.94	0.94

Table 3 Average annual generated energy at each country for irrigation development sceanrio, and integrated transboundary and unilateral system management

Simulation case / scenario	Ethiopia		Sudan		Egypt	
	Coop (GWh/yr)	Non-Coop (GWh/yr)	Coop (GWh/yr)	Non-Coop (GWh/yr)	Coop (GWh/yr)	Non-Coop (GWh/yr)
S0	1040	1040	7635	7635	11600	11600
S10	16,865	16,865	8,951	8,951	11,676	11,768
S11	16,950	16,947	8,369	8,471	10,157	10,428
S20	35,260	36,034	9,273	9,081	11,777	11,698
S21	35,235	36,035	7,892	8,652	9,394	9,097
S30	35,260	36,034	15,220	15,074	11,875	12,064
S31	23,604	36,035	13,129	15,001	9,919	10,897

Table 4 Monthly irrigation supply reliability (average monthly supply to demand ratio (%)) of irrigation schemes in countries

Simulation Case/scenario	Integrated transboundary system management			Unilateral management		
	Supply/ Demand ratio (%)			Supply/ Demand ratio (%)		
	Ethiopia	Sudan & S. Sudan	Egypt	Ethiopia	Sudan & S. Sudan	Egypt
S0	---	99	100	---	99	100
S10	---	100	99	---	98	99
S11	96	99	95	97	98	95
S20	---	97	100	---	98	99
S21	72	92	91	100	93	88
S30	---	96	100	---	93	99
S31	72	90	92	100	80	97

Figure 1 Eastern Nile Sub-basins and reservoir system

Figure 2 Measured and simulated flow at key locations in the Blue Nile, Atbara River and the main Nile at years of different hydrologic conditions: dry (Jul 1984-Jun 1985), normal (Jul 1977-Jun 1978) and wet (Jul 1988-Jun1989).

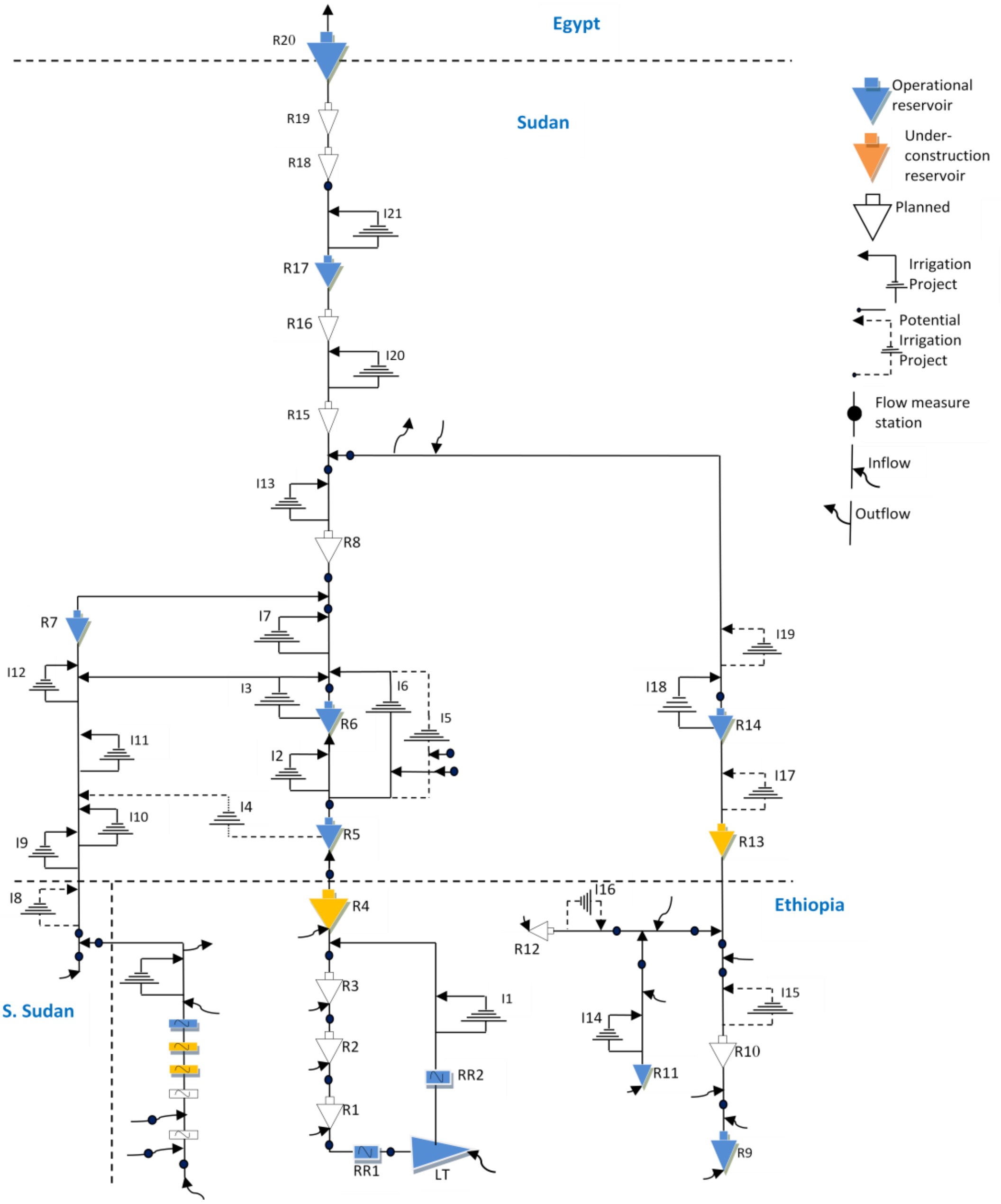
Figure 3: Box plot of the annual generated energy (GWh/year) of the basin countries for each GERD dam development (S1xx) scenario, with (Sx0x) and without(Sx1x) irrigation development in case the system is managed ìn an integrated manner (Sxx0) and unilaterally (Sxx1).

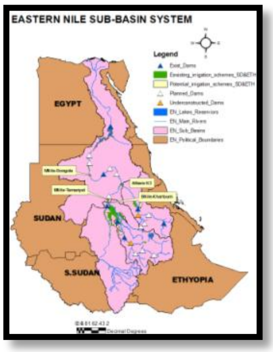
Figure 4 Non exceedance probability of the average monthly supply to demand ratio (%) of Sudan existing(Sx0x) and potential (Sx1x) irrigation projects after GERD development (S1xx) under integrated system management (Sxx0), unilateral management (Sxx1) and Base.

Figure 5: Average annual net evaporation from reservoirs under integrated and unilateral management for the system, with and without irrigation development of: (a) Ethiopia, (b) Sudan, (c) Egypt, (d) entire basin.

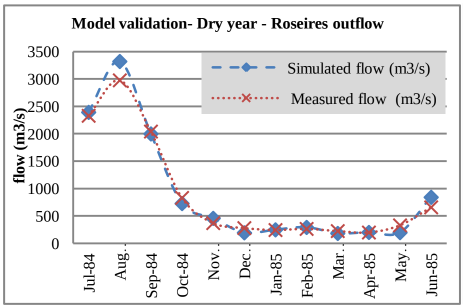
Figure 6 Average monthly flow [m3/s] at (a) Sudanese Egyptian border [Aswan High Dam (AHD)] and (b) Sudanese Ethiopian border [Border (Eldiem)] when GERD gets operational (S1xx), with existing (Sx0x) and potential (Sx1x) irrigation projects under integrated (Sxx0) and unilateral (Sxx1) system management.

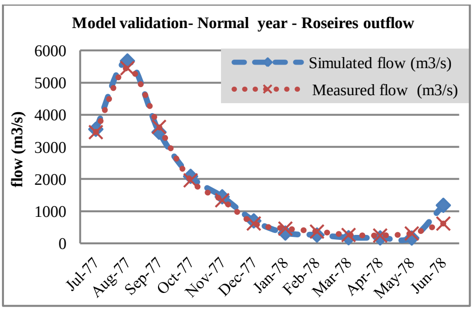
Figure 7 Cumulative distribution function (CDF) of the annual stream flow at (a) AHD and (b) Border when GERD gets operational (S1xx), with existing (Sx0x) and potential (Sx1x) irrigation projects under integrated (Sxx0) and unilateral (Sxx1)system management.

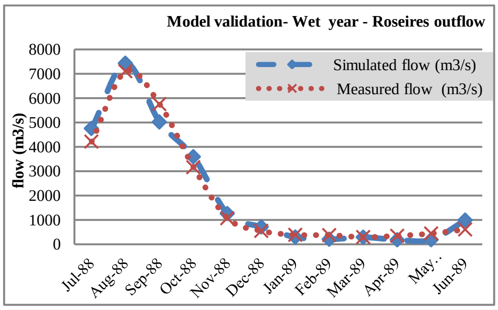


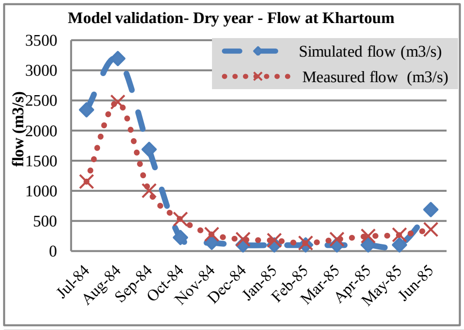


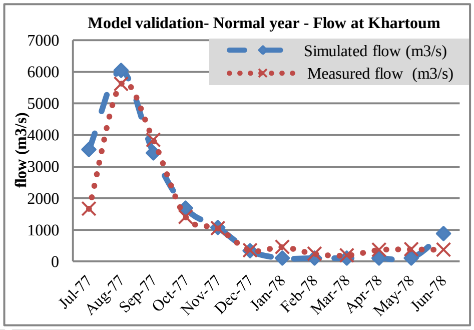
LT	LTana_Charachara(E)	R11	Atbr_smalIrr_Ir(E)- Angereb River	RR2	BN_TanaBeless_Hp(E)	I11	WN_WNPrjcts-sonds(E)
R1	BNile_Karadobi_Hp(P)	R12	Atb_Metama_Hp(P)	I1	BN_BelesUpprLowr(E)	I12	WN_WNileSuger(P)
R2	BNile_BekoAbo Hp(P)	R13	Atb_Settit_IrHp(P)	I2	BN_UpSennar(E)	I13	MN_Atbara(E)
R3	BNile_Mendaya_Hp(P)	R14	Atb_KGirba_IrHp(E)	I3	BN_GeziraMenagil(E)	I14	Atb_smallscale(E)
R4	BNile_GERD Hp(P)	R15	MNile_Sheriq_Hp(P)	I4	BN_Kenana(K1-K4)(P)	I15	Atb_Hummera(P)
R5	BN_Roseires_IrHp(E)	R16	MNile_Mograt_Hp(P)	I5	BN_Rahad-2(P)	I16	Atb_Metema(P)
R6	BNile_Sennar_IrHp(E)	R17	MNile_Merowe_IrHp(E)	I6	BN_USennarRahad-I(E)	I17	Atb_Settit(P)
R7	WNile_JAulia_IrHp(E)	R18	MNile_Kajabar_Hp(P)	I7	BN_GinaidBNpumps(E)	I18	Atb_NewHalfa(E)
R8	MNile_Sbloga_IrHp(P)	R19	MNile_Dal_Hp(P)	I8	WN_Malakal-Melut(P)	I19	Atb_UpperAtbara(P)
R9	Atb_TK5_Hp(E)	R20	MNile_AHD_Hp(E)	I9	WN_Kenana-I(E)	I20	MN_PumpScheme(E)
R10	Atb_Humera_IrHp(P)	RR1	BN_TissAbbay_Hp(E)	I10	WN_AsalyaSuger(E)	I21	MN_Merowe(E)

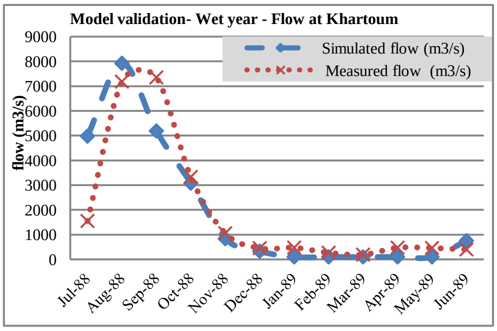

Model validation- Dry year - Roseires outflow

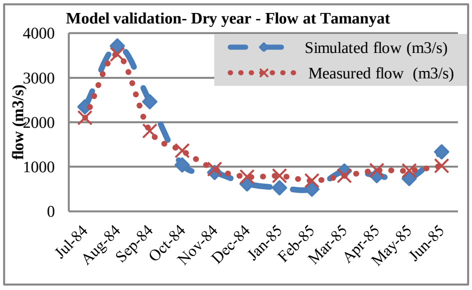

Model validation- Normal year - Roseires outflow

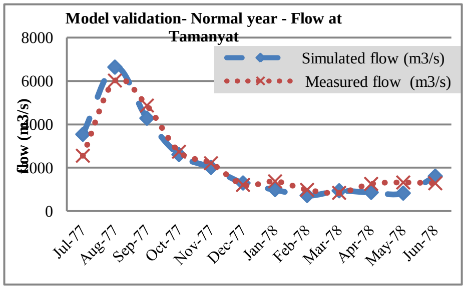

Model validation- Wet year - Roseires outflow

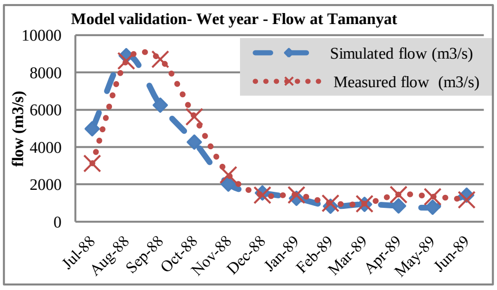

Model validation- Dry year - Flow at Khartoum

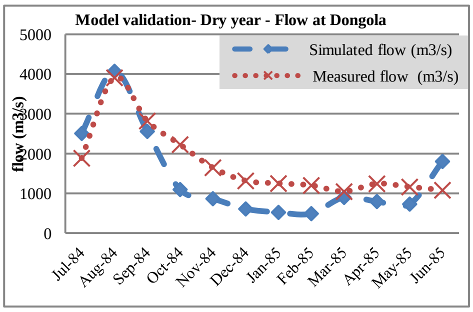

Model validation- Normal year - Flow at Khartoum

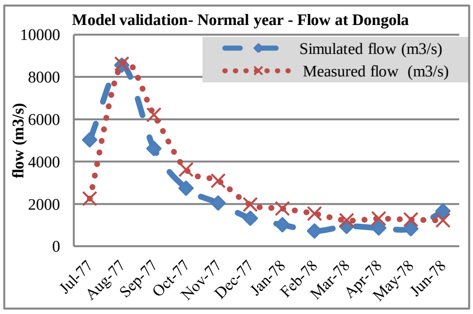

Model validation- Wet year - Flow at Khartoum

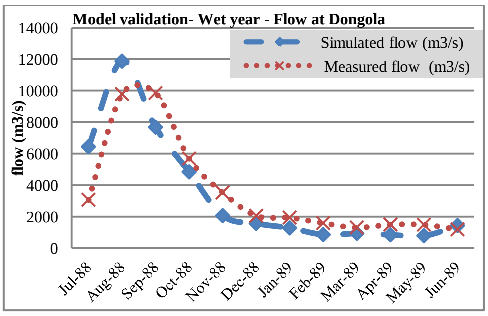

Model validation- Dry year - Flow at Tamanyat

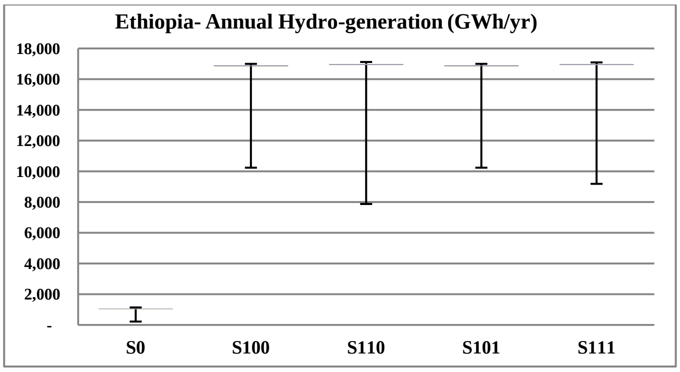

Model validation- Normal year - Flow at Tamanyat


Model validation- Wet year - Flow at Tamanyat

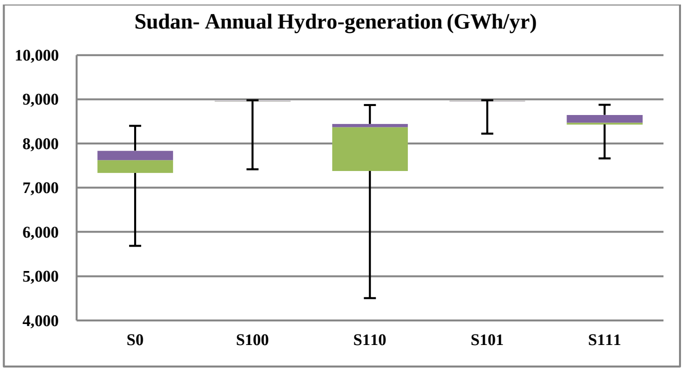

Model validation- Dry year - Flow at Dongola


Model validation- Normal year - Flow at Dongola

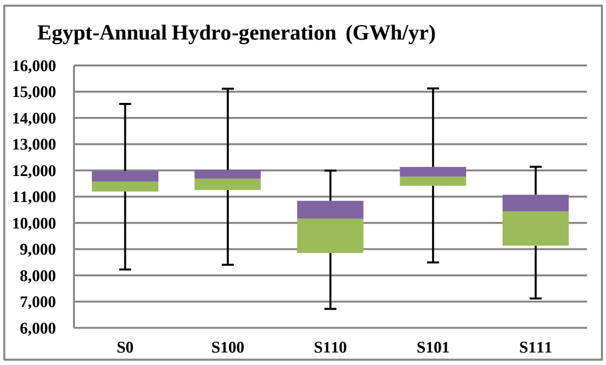

Model validation- Wet year - Flow at Dongola


Ethiopia- Annual Hydro-generation (GWh/yr)
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
S0
S100
S110
S101
S111

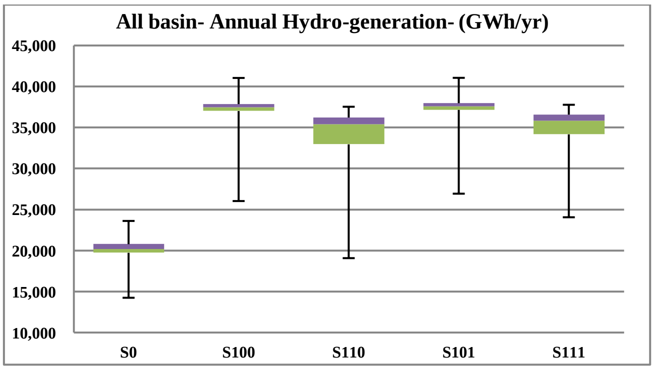
(a)


Sudan- Annual Hydro-generation (GWh/yr)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
S0
S100
S110
S101
S111

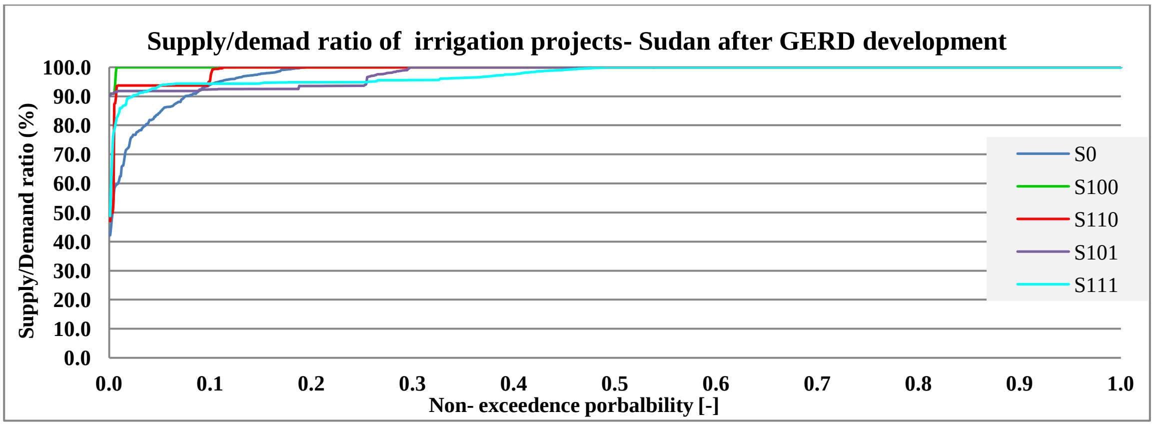
(b)

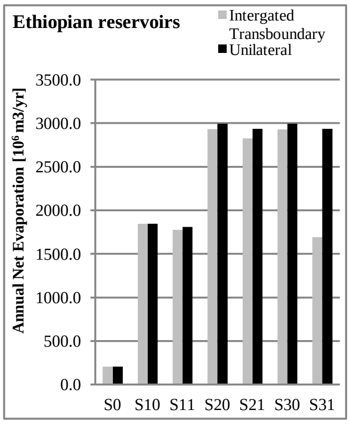

Egypt-Annual Hydro-generation (GWh/yr)
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
S0
S100
S110
S101
S111

(c)

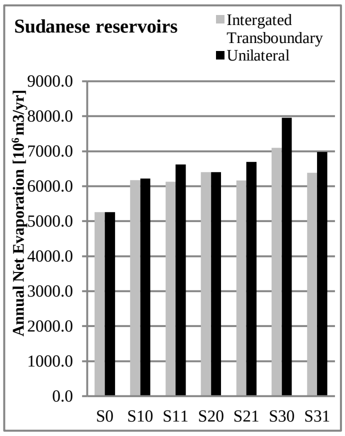

All basin- Annual Hydro-generation- (GWh/yr)
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
S0
S100
S110
S101
S111

(d)

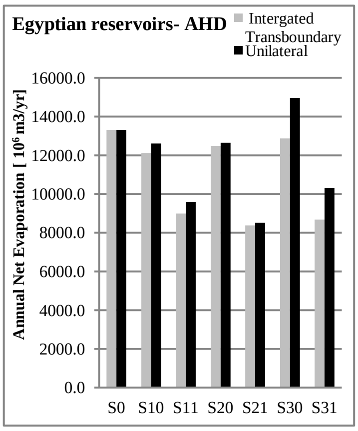

Supply/demad ratio of irrigation projects- Sudan after GERD development
Supply/Demand ratio (%)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Non- exceedence porbalbility [-]
S0
S100
S110
S101
S111


Ethiopian reservoirs
Intergated Transboundary
Unilateral
Annual Net Evaporation [10^6 m3/yr]
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
S0
S10
S11
S20
S21
S30
S31

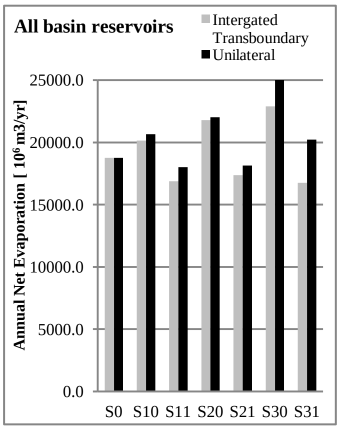
(a)


Sudanese reservoirs
Intergated Transboundary
Unilateral
Annual Net Evaporation [10^6 m3/yr]
9000.0
8000.0
7000.0
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
S0
S10
S11
S20
S21
S30
S31

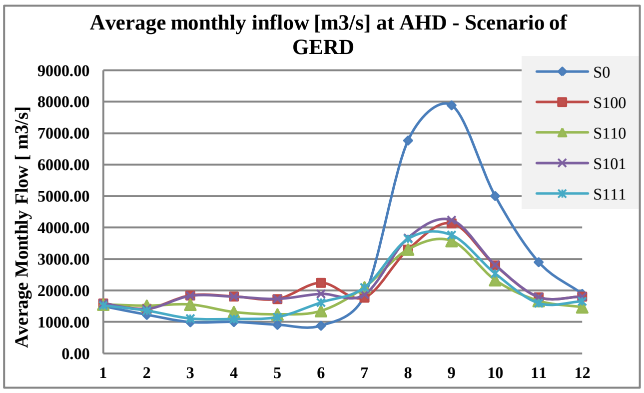
(b)


Egyptian reservoirs- AHD
Intergated Transboundary
Unilateral
Annual Net Evaporation [10^6 m3/yr]
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
S0
S10
S11
S20
S21
S30
S31

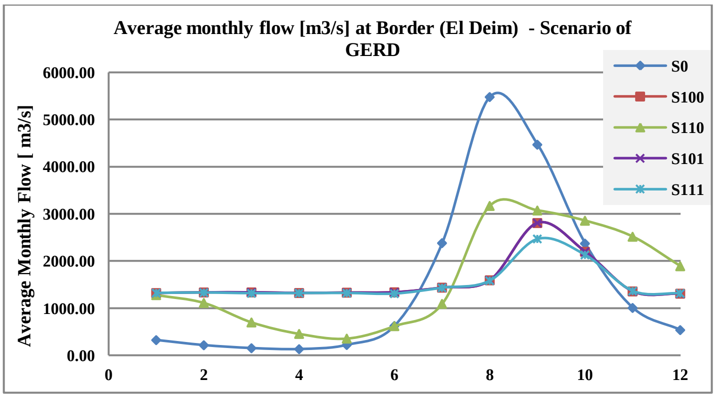
(c)


All basin reservoirs
Intergated Transboundary
Unilateral
Annual Net Evaporation [10^6 m3/yr]
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
S0
S10
S11
S20
S21
S30
S31

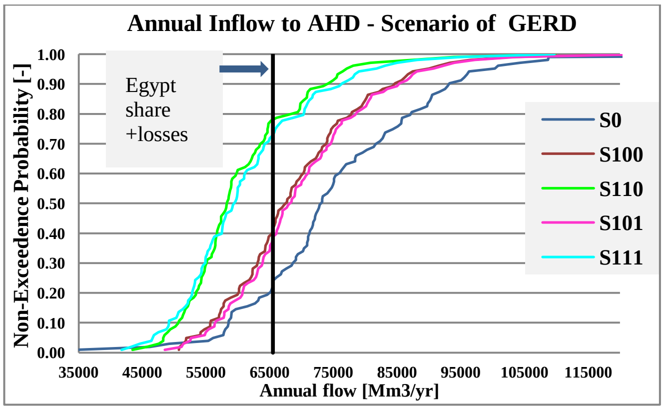
(d)


Average monthly inflow [m3/s] at AHD - Scenario of GERD
Average Monthly Flow [m3/s]
9000.00
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
S0
S100
S110
S101
S111

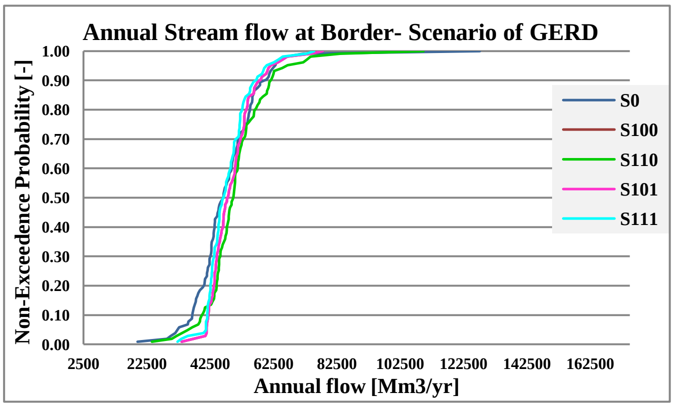
(a)


Average monthly flow [m3/s] at Border (El Deim) - Scenario of GERD
Average Monthly Flow [m3/s]
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
0
2
4
6
8
10
12
S0
S100
S110
S101
S111

(b)


Annual Inflow to AHD - Scenario of GERD
Non-Exceedence Probability [-]
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Egypt share +losses
35000
45000
55000
65000
75000
85000
95000
105000
115000
Annual flow [Mm3/yr]
S0
S100
S110
S101
S111

(a)


Annual Stream flow at Border- Scenario of GERD
Non-Exceedence Probability [-]
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2500
22500
42500
62500
82500
102500
122500
142500
162500
Annual flow [Mm3/yr]
S0
S100
S110
S101
S111

(b)

Appendix

Table 5 Major Reservoirs, Hydropower Plants and Irrigation Projects in the Eastern Nile (Source: Verhoeven (2011); Goor (2010); ENTRO (2007)).

Project name	Status	Current capacity [Potential capacity] (MW)	Reservoir capacity [Potential capacity] (m^3) Irrigation area (ha)
Ethiopia			
Tekeze River			
Tekeze V	Operating since 2009	300	9.293 x10^9 45,000
Tekeze II	Proposed, 2020 Expected year of commission	[450]	Not Available
Lake Tana Tributaries			
Tana Beles (Lake Tana- Beles River Transfer)	Operating since 2010	460	9.12 x10^9 [140,000-150,000]
Abbay(Blue Nile)			
Tis Abbay I, Abbay River	Operating since 1964	11.4	[50,000]
Tis Abbay II, Abbay River	Operating since 2001	68-85	
Fincha' a , Fincha' a River	Operating since 1973, Extra unit added and commissioned 2006	128-134	460 x10^6 - 2.4 x10^9
Fincha'a-Amerti-Neshi, Fincha' a River	Under construction, 57% completed as of April 2011	[97]	-
Grand Ethiopian Renaissance Dam, Blue Nile	Under construction, started April 2011, expected complete date in 2017	[5,250]	[63-67 x10^9] updated to [74 x10^9]
Chemoga- Yeda Hydropower Project, including dams on Chemoga, Yeda, Sens, Getla, Bogrna	Construction contract signed. Expected completion of Phase I in 2015.	[278]	-----
Jema, Jema River	Proposed, Feasibility study complete	----	[173 x10^6] [7,800]
Mabil, Blue Nile (replaced by Beko Abo Dam)	Proposed, 2021Expected year of commission	[1,200]	[13.6 x10^9]
Mendaya/Mendaya, Blue Nile	Proposed under ENSAP, Nile Basin Initiative , 2030 Expected year of commission	[1,620-2,000]	[13 x10^6 -15.9 x10^6]
Beko Abo, Blue Nile	Proposed under ENSAP, Nile Basin Initiative.	[2,100]	10.5 x10^6
Border, Blue Nile (replace d by GERD)	Proposed under ENSAP, Nile Basin Initiative, 2026 Expected year of commission	[800-1,400]	[11.1 x10^9]
Karadobi, Blue Nile	Proposed under ENSAP, Nile Basin Initiative, 2023 Expected year of commission	[1000-1,600]	[32.5- 41 x10^9]
Diddessa irrigation project, including dams on Diddessa, Dabana, Negeso	Proposed, 2038 Expected year of commission	[308- 615]	[55,000]
Anger- Nekemte Irrigation Project, including dams on Anger, Nekemte	Proposed, 2038 Expected year of commission	[15-20]	[26,000]
Dabus, Dabus River	Proposed, feasibility studies ongoing	[425]	----------

Baro River and its tributaries			
Sor, tributary of Geba	Operating since 1990	5	----------------
Alwero Irrigation Project, Alwero river	Operating since 1995	Not Available	74,600
BaroI and II, Baro River	Proposed under ENSAP, Nile Basin Initiative, 2034 Expected year of commission	[850-896]	---------
Geba I and II, Geba River	Proposed under ENSAP, Nile Basin Initiative, 2016 Expected year of commission	[254 - 366]	-----------
Birbir A and B	Proposed, feasibility studies ongoing	[467 - 508]	---------------
Tams	Proposed, feasibility studies ongoing	[1,000]	------------------
Sudan			
Main Nile			
Merowe, 4th Cataract, Nile	Operating since 2009	1,250 [2,000]	12.5 x10^{9} 380,000
Kajbar, 3rd Cataract, Nile	Under construction, 2016 Expected year of commission	[300–360]	8.2 x10^{6}
Shereik ,3rd Cataract, Nile	Construction contract signed	[315–420]	------------
Dal ,2nd Cataract, Nile	Proposed, Feasibility studies ongoing	[340–600]	------------
Mograt ,4th Cataract, Nile	Proposed, Feasibility studies complete	[240-312]	----------------
Dagash, Main Nile		[285-312]	------------------
Sabaloka, 6th Cataract, Nile		[120-205]	[4 x10^{9}]
Atbara River and tributaries			
Khashm Elgirba Atbara River	Operating since 1964	0–7 [12.5]	1.3 x10^{9} 206,640
Upper Atbara Project, including Rumela Dam in Atbara River, Burdana Dam in Settit River	Under construction, 2015 Expected year of commission	Rumela [120] Burdana [15]	[2.7 x10^{9}] Rumela [190,000] Burdana[210,000]
Blue Nile			
Roseires Dam, Blue Nile	Operating since1966; 1971 Hydropower plant added; 2013 Estimated completion of dam heightening	100–250 [275]	2.2 x10^{9} [3.7–4 x10^{9}] 1.7 x10^{6}
Sennar Dam, Blue Nile	Operating since 1925; 1962 Hydropower plant added; Rehabilitation planning ongoing	15 [45]	[640 x10^{6}] [930 x10^{6}] 870,750
White Nile			
Jebel Aulia, White Nile	Operated since 1937 Rehabilitated in 2005	30.4-35	3.5 x10^{9} 152,280
Egypt			
Main Nile			
High Aswan Dam	Operating	2100	162x10^{9}
Old Aswan Dam	Operating	500	0(run of river) No irrigation
Esna	Operating	90	0(run of river) No irrigation
Assyut	Operating	[32]	0(run of river) 690 x10^{3}
Delta	Operating	----	0(run of river) 305 x10^{3}
Naga Hammadi	Operating	64	0(run of river)

			320 x10^3

4

Supplemental Data

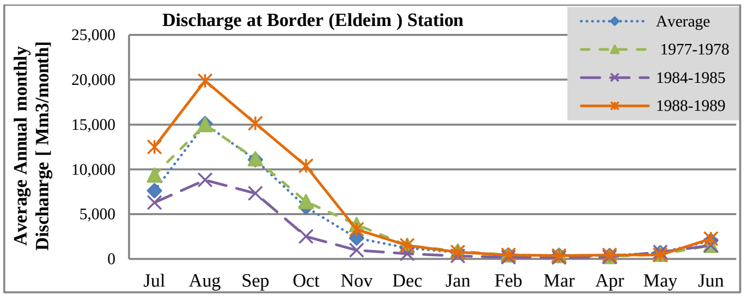


Figure S1: Average annual monthly discharge (July- June) at Border (Eldiem) station

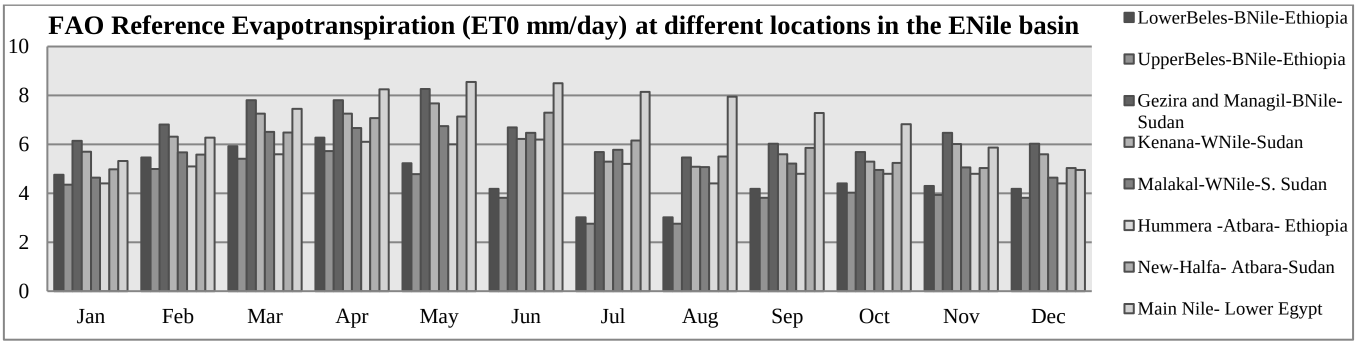


Figure S2 The monthly reference evapo-transpiration (ET_0) at different locations in the Eastern Nile basin

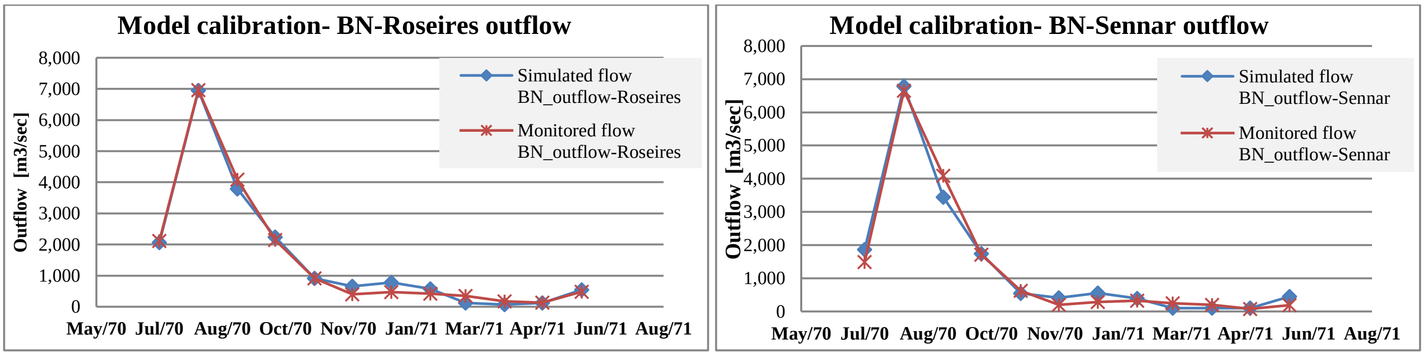


Figure S3 Measured and Simulated downstream flow (m^3/sec) at Roseires and Sennar dams (Jul 1970-Jul 1971)

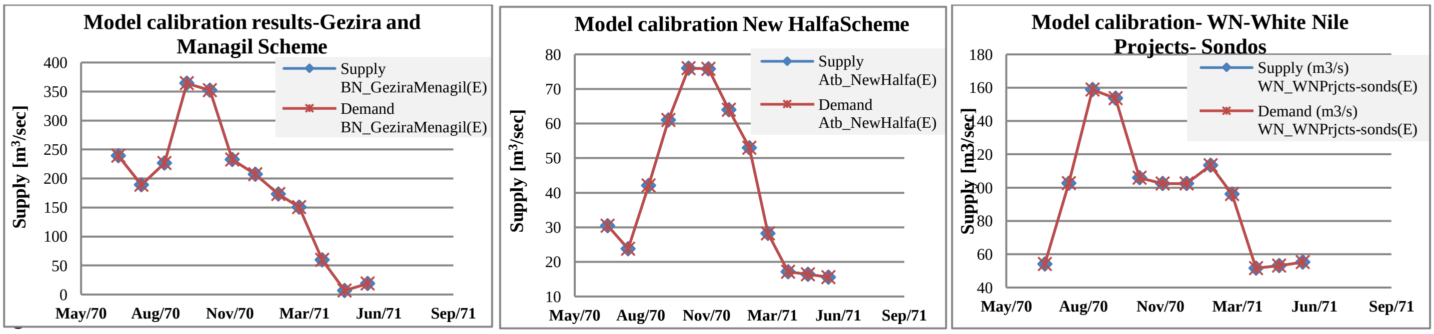


Figure S4 Demand (m^3/sec) and the Supply (m^3/sec) of Gezira and Managil, New Halfa and White Nile Irrigation Project (Jul 1970-Jul 1971)

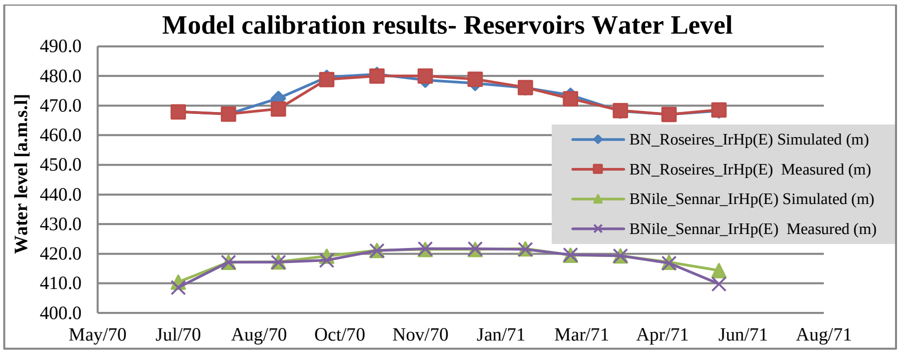


Figure S5 Measured and Simulated water levels (a.m.s.l) at Roseires and Sennar dams (Jul 1970-Jul 1971)

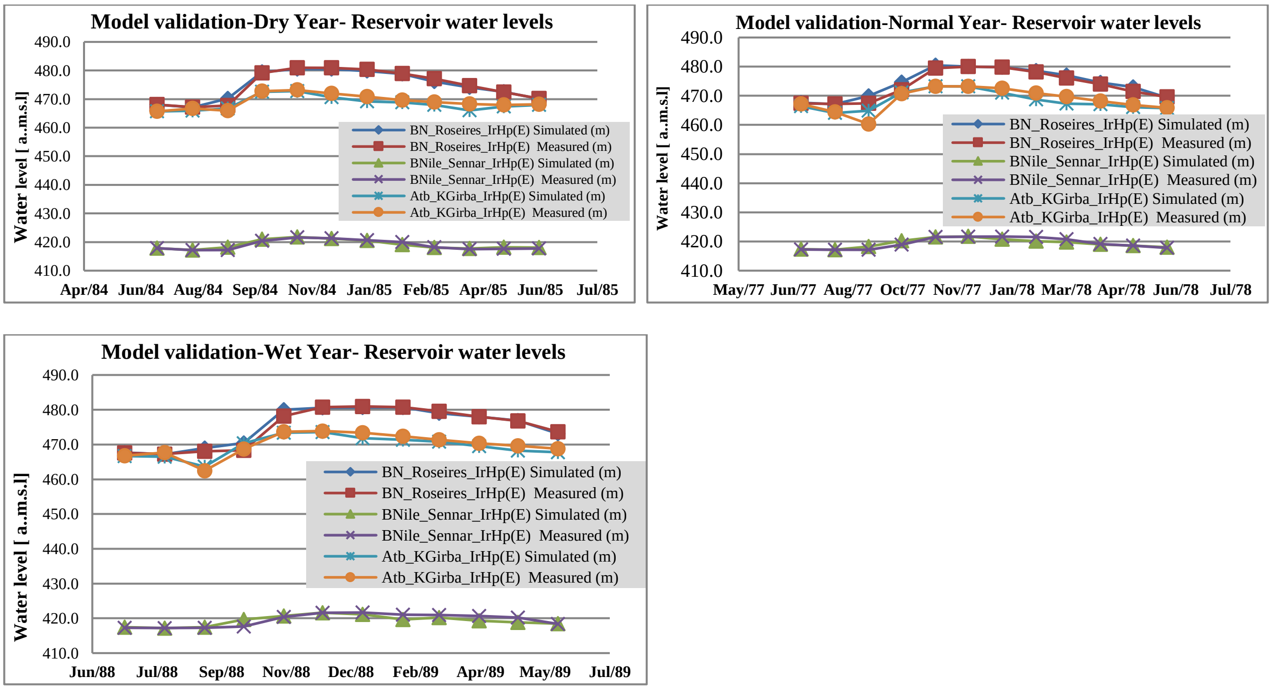


Figure S6 Measured and Simulated water levels (a.m.s.l) of Roseires, Sennar and Khashm Elgirba dams at years **of different hydrologic conditions: dry (Jul 1984-Jun 1985), normal (Jul 1977-Jun 1978) and wet (Jul 1988-Jun1989)**

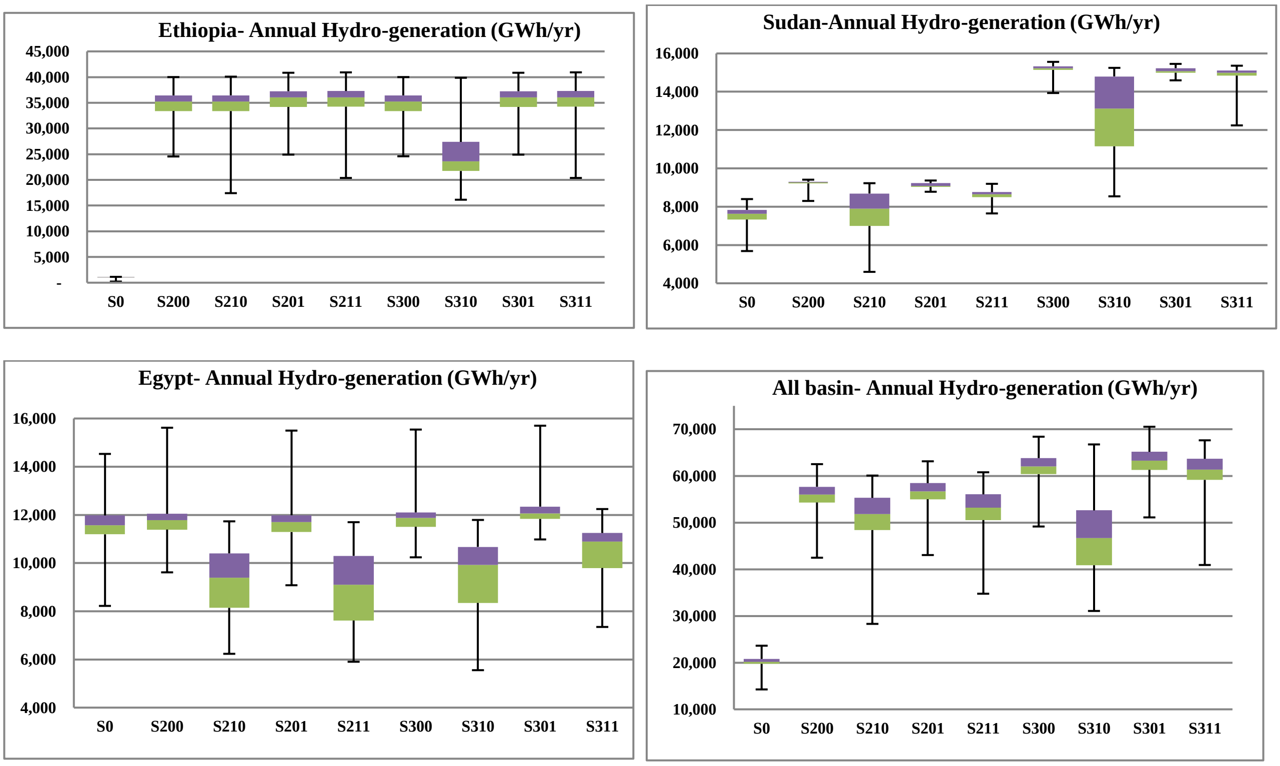
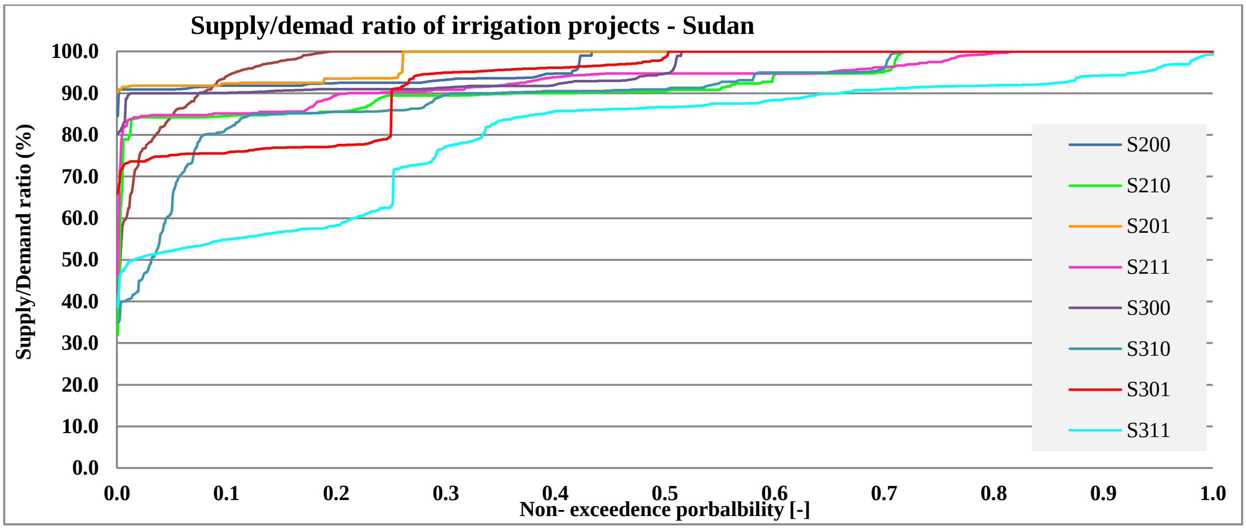


Figure S7: Box plot of the annual generated energy (GWh/year) of the basin countries for Ethiopian dam(S2xx) and full basin (S3xx) development scenarios, with (Sx0x) and without (Sx1x) irrigation development in case of integrated transboundary (Sxx0) and unilateral (Sxx1) system management.



FiguFigure S8: Non exceedance probability of the average monthly supply to demand ratio (%) of Sudan existing (Sx0x)and potential (Sx1x) irrigation projects after Ethiopian dams (S2xx) and basin full (S3xx) development under integrated transboundary management (Sxx0), unilateral management (Sxx1) and Base Scenario (S0)

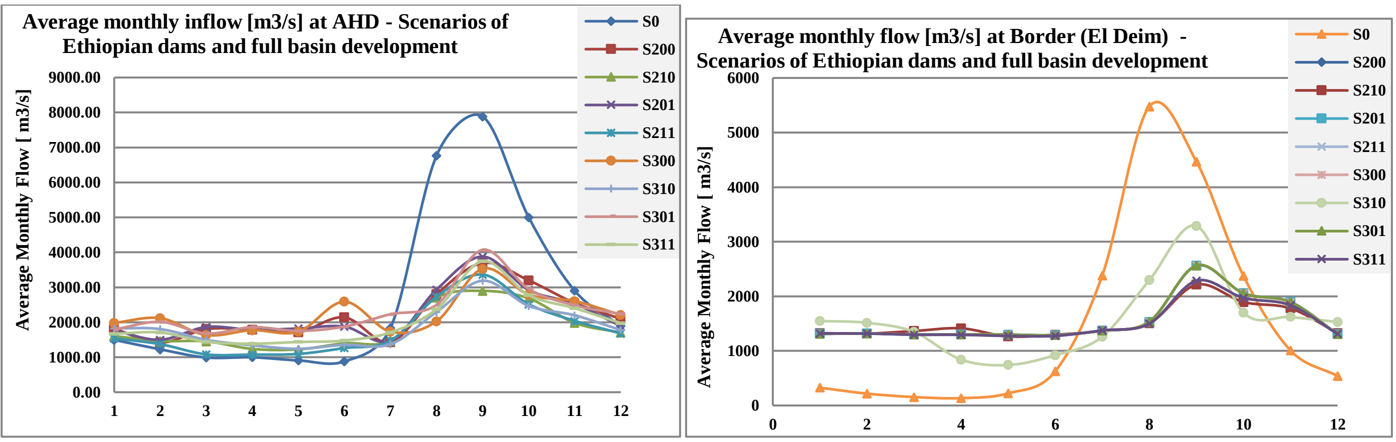


Figure S9 Average monthly flow[m3/s] at (a) AHD and (b) Border after Ethiopian dams (S2xx) and basin full (S3xx) development, with existing (Sx0x) and potential (Sx1x) irrigation projects under integrated transboundary (Sxx0) and unilateral (Sxx1)system management

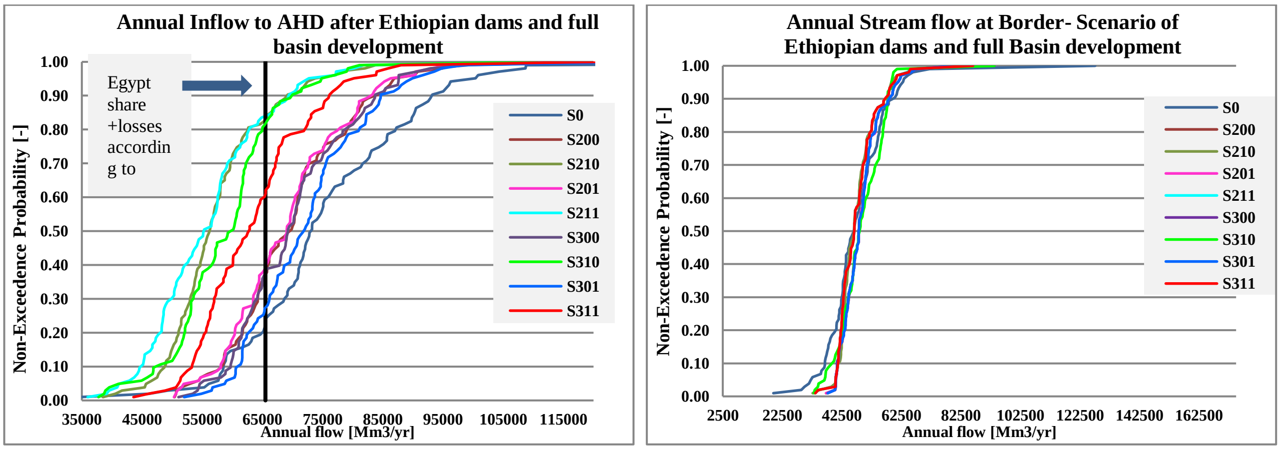


Figure S10 Cumulative distribution function (CDF) of the annual stream flow at (a) AHD and (b) Border after Ethiopian dams (S2xx) and basin full (S3xx) development, with existing (Sx0x) and potential (Sx1x) irrigation projects under integrated transboundary (Sxx0) and unilateral (Sxx1)system management

Table S1 Hedging rules for model calibration

Hedging rules		
Storage zones between firm and dead storage	Lower boundary of zone [% between firm and dead storage]	Water allocation [% of target release]
-	100	-
Zone 1	80	90
Zone 2	60	70
Zone 3	40	50
Zone 4	20	30
Zone 5	0	10

Table S2 Irrigation Projects data used for model calibration

Month	BN_GeziraMenagil(E) Mm3/month[1]	Atb_NewHalfa(E) Mm3/month[2]	WN_WNPrjcts-sonds(E) Mm3/month[2]
Jul-1970	640.66	81.45	144.61
Aug-1970	507.00	63.70	274.93
Sep-1970	586.54	109.14	411.54
Oct-1970	974.82	163.42	411.54
Nov-1970	912.15	197.05	274.36
Dec-1970	622.23	203.10	274.36
Jan-1971	555.39	171.25	274.36
Feb-1971	418.39	128.27	274.14
Mar-1971	403.29	75.70	257.21
Apr-1971	153.88	44.46	133.86
May-1971	18.44	43.86	142.32
Jun-1971	49.06	40.42	143.26

1: Source: Estimated from Roseires Heightening Report (McLellan, 1987) and MWRE-Dams Operation Department

3: Source: Nile Water Master Plan (MOI, 1979) and MWRE-Nile Water Directorate 2014

Table S3 Irrigation Projects data used for model validation- Dry Year (July 1984-June1985)

Month	BN_GeziraMenagil(E) Mm3/month[1]	BN_USennarRahad-I(E) Mm3/month[1]	BN_UpSennar (E) Mm3/month[2]	BN_GinaidBNpumps(E) Mm3/month[2]	Atb_NewHalfa(E) Mm3/month[3]	WN_AsalyaSuger(E) Mm3/month[3]	WN_Kenana-I(E) Mm3/month[2]	WN_WNPrjcts-sonds(E) Mm3/month[3]
Jul-1984	559.70	112.27	63.72	133.96	133.96	17.00	89.81	176.43
Aug-1984	873.47	192.49	85.30	186.18	186.18	22.67	72.14	224.03
Sep-1984	872.11	202.17	84.10	222.35	222.35	17.35	68.79	307.64
Oct-1984	827.91	172.95	74.55	179.02	179.02	21.15	63.11	295.95
Nov-1984	585.78	122.18	95.58	133.24	133.24	21.04	81.67	298.38
Dec-1984	482.18	109.33	83.62	116.40	116.40	17.23	69.97	283.95
Jan-1985	368.32	95.57	62.56	72.99	72.99	15.71	63.55	299.73
Feb-1985	337.06	85.93	57.54	37.05	37.05	19.32	66.54	145.37
Mar-1985	78.26	13.86	37.70	37.49	37.49	18.05	60.10	126.84
Apr-1985	31.10	0.00	54.96	41.66	41.66	16.86	90.56	114.74
May-1985	32.96	0.00	36.39	80.25	80.25	19.94	88.56	116.67
Jun-1985	332.42	136.88	36.76	165.54	165.54	19.95	77.30	143.54

1: Source: Roseires Heightening Report (McLellan, 1987)

2: Source: Long term Power plan and MWRE-Nile Water Directorate 2014

3: Source: Nile Water Master Plan (MOI, 1979) and MWRE-Nile Water Directorate 2014

Table S4 Irrigation Projects data used for model validation- Normal Year (July 1977-June1978)

Month	BN_GeziraMenagil (E) Mm3/month[1]	BN_USennarRahad-I (E) Mm3/month[1]	BN_UpSennar (E) Mm3/month[2]	BN_GinaidBNpumps (E) Mm3/month[2]	Atb_NewHalfa (E) Mm3/month[3]	WN_WNPrjcts-sonds (E) Mm3/month[3]
Jul-1977	529.28	54.20	86.54	35.06	122.08	166.13
Aug-1977	856.10	14.92	8.87	22.82	68.58	210.95
Sep-1977	870.73	67.98	42.74	36.30	172.28	280.34
Oct-1977	862.89	70.95	105.64	42.30	229.65	278.67
Nov-1977	809.55	59.76	106.58	38.97	225.24	271.89
Dec-1977	814.60	51.40	83.08	37.37	199.84	267.37
Jan-1978	803.71	36.20	73.21	34.21	167.84	267.37
Feb-1978	449.57	29.40	107.21	32.91	132.60	117.13
Mar-1978	88.33	5.25	55.40	38.58	72.49	113.15
Apr-1978	36.55	0.00	39.15	25.74	43.80	99.05
May-1978	38.73	0.00	35.99	22.69	45.05	100.72
Jun-1978	661.43	1.25	34.56	30.86	83.99	128.04

1: Source: Roseires Heightening Report (McLellan, 1987)

2: Source: Long term Power plan and MWRE-Nile Water Directorate 2014

3: Source: Nile Water Master Plan (MOI, 1979) and MWRE-Nile Water Directorate 2014

Table S5 Irrigation Projects data used for model validation- Wet Year (July 1988-June1989)

Month	BN_GeziraMenagil(E) Mm3/month[1]	BN_USennarRahad-I(E) Mm3/month[1]	BN_UpSennar (E) Mm3/month[2]	BN_GinaidBNpumps(E) Mm3/month[2]	Atb_NewHalfa(E) Mm3/month[3]	WN_AsalyaSuger(E) Mm3/month[3]	WN_Kenana-I(E) Mm3/month[2]	WN_WNPrjcts-sonds(E) Mm3/month[3]
Jul-1988	525.00	75.60	32.05	22.61	173.67	34.70	65.41	176.10
Aug-1988	477.49	30.10	49.52	8.80	16.23	61.60	55.10	196.20
Sep-1988	512.95	181.04	45.50	37.94	99.46	8.80	56.60	217.00
Oct-1988	824.10	150.50	85.36	28.32	218.80	12.97	62.10	250.00
Nov-1988	779.03	180.83	106.83	29.30	206.87	20.82	81.40	248.31
Dec-1988	775.60	115.30	55.56	27.04	183.20	16.62	70.20	250.15
Jan-1989	564.90	70.14	57.43	23.02	143.40	14.67	64.19	270.35
Feb-1989	545.71	55.80	52.74	20.39	124.33	15.62	67.88	101.41
Mar-1989	363.10	30.15	43.48	20.26	95.00	15.00	61.47	110.50
Apr-1989	88.45	39.58	40.34	23.44	55.86	19.58	89.07	99.36
May-1989	69.75	31.30	59.80	21.83	52.88	25.00	89.00	96.75
Jun-1989	195.71	59.02	99.30	30.55	52.29	19.57	79.26	124.41

1: Source: Estimated from Roseires Heightening Report (McLellan, 1987) and MWRE-Nile Water Directorate 2014

2: Source: Long term Power plan and MWRE-Nile Water Directorate 2014

3: Source: Nile Water Master Plan (MOI, 1979) and MWRE-Nile Water Directorate 2014

Table S6 Reservoir Level- Area- Volume data used for calibration and validation

Process	Year	Roseires	Sennar	K.Girba	J.Aulia
Calibration	Jul1970-Jun1971	1966 Bathymetric data	1925 Bathymetric data	1964 Bathymetric data	1937 Bathymetric data
Validation	Jul1977-Jun1978	1966 Bathymetric data	1925 Bathymetric data	1964 Bathymetric data	1937 Bathymetric data
	Jul1984-Jun1985	1985 Bathymetric data	1985 Bathymetric data	1978 Bathymetric data	1937 Bathymetric data
	Jul1988-Jun1989	1985 Bathymetric data	1985 Bathymetric data	1978 Bathymetric data	1937 Bathymetric data