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The question of Sudan: a hydroeconomic optimization model for the Sudanese Nile

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Abstract

The effects of development and the uncertainty of a changing climate in East Africa pose myriad challenges for water managers along the Blue Nile. Sudan's large irrigation potential, hydroelectric dams, and prime location within the basin mean that Sudan's water management decisions will have great social, economic and political implications within the region. At the same time, Sudan's water use options are constrained by tradeoffs between upstream irrigation developments and downstream hydropower facilities as well as by the country's commitments under existing or future transboundary water sharing agreements. Here, we present a model that can be applied to evaluate optimal allocation of surface water resources to irrigation and hydropower in the Sudanese portion of the Blue Nile. Hydrologic inputs are combined with agronomic and economic inputs to formulate an optimization model within the General Algebraic Modeling System (GAMS). A sensitivity analysis is performed by testing model response to a range of economic conditions and to changes in the volume and timing of hydrologic flows. Results indicate that changing hydroclimate inputs have the capacity to greatly influence the productivity of Sudan's water resources infrastructure. Results also show that the economically optimal volume of water consumption, and thus the importance of existing treaty constraints, is sensitive to the perceived value of agriculture relative to electricity as well as to changing hydrological conditions.

1 Introduction

The Nile Basin spans parts of 11 different countries in one of the most underdeveloped regions in the world. The transboundary nature of the Nile presents water-sharing challenges between upstream and downstream riparian nations (Waterbury et al., 1998). This is particularly true in the Eastern Nile basin, which is typically defined as the tributaries that arise in the Ethiopian Highlands – primarily the Blue Nile, Tekeze-Atbara, and Baro-Akobo-Sobat – together with the main stem Nile north of Khartoum (Fig. 1).

The Eastern Nile tributaries collectively contribute over 80 % of flow in the main stem Nile. The Eastern Nile basin also exhibits strong hydrological connectivity, in that upstream climate variability and development directly impact downstream resources in a manner that is not observed in the White Nile system, where lakes and wetlands serve as a buffer between the Equatorial Lakes headwaters region and downstream water deficit areas in Sudan and Egypt (Blackmore and Whittington, 2008). For this reason the utilization of Eastern Nile waters has long been a source of transboundary tension, most notably between Egypt, which claims historical rights to the majority of Nile River water, and Ethiopia, which has a strong interest in developing the Eastern Nile tributaries for hydropower and other uses.

While the diplomatic tensions between Egypt and Ethiopia have dominated the political and media discourse on Eastern Nile basin development (Cascao, 2008; Igunza, 2014; Hussein, 2014; Gebreluel, 2014), Sudan has the greatest potential to influence transboundary distribution of water resources. The 1959 Nile Waters Agreement grants Sudan the right to use 18.5 billion cubic meters (bcm) of Nile water per year. At present, however, Sudan uses far less than this allocation; its actual water use has been estimated to be approximately 13.5 bcm year^{-1} (Blackmore and Whittington, 2008). This fact is surprising, given Sudan's vast areas of irrigable land and prevailing aridity, and has been attributed to policy and management issues combined with the difficulty of establishing infrastructure and practices that make efficient use of the highly variable and silt-laden flows of the Blue Nile. All of these factors could change in the future, both through internal development decisions and though external influences such as climate change and upstream infrastructure in Ethiopia. Where climate change has the potential to alter the magnitude of Blue Nile inflow and local evaporative demand, upstream infrastructure would be expected to regularize the timing of flows and to reduce silt load entering Sudan.

In this context, there is a need for analysis tools focused on Sudan's hydrodevelopment options. In particular, it is important to understand how impending changes affecting the Sudanese portion of the Eastern Nile basin, including climate change and upstream development in Ethiopia, are likely to affect Sudan's use of its Nile River resources for hydropower and irrigation. The objective of this paper is to present an optimization model that illustrates the sensitivities of Sudan's Blue Nile and main stem Nile water resources infrastructure to changes in climate and upstream development. For purposes of this sensitivity analysis we assume no change in prevailing agricultural practices or in Sudanese infrastructure, so the simulations can be interpreted as evaluations of the influence that external changes would have on Sudan given current conditions and in the absence of large-scale adaptive action.

1.1 The Blue Nile in Sudan

Approximately 60 bcm of water flows annually from the Blue Nile basin in Ethiopia to Sudan. Inter-seasonal variability is large, with flows peaking in August and September, and inter-annual variability is also considerable – gauged flow at Roseries (Fig. 1) has an inter-annual variability equal to 25 % of the mean flow. The basin is also undergoing climate change that has had a significant impact on temperature but, as of yet, no clear directional impact on total annual precipitation or river discharge. In coming decades, climate change impacts on basin hydrology are expected to become more significant.

The magnitude, seasonality, and even directionality of this change, however, are highly uncertain. Global Climate Models (GCM's) participating in the 5th Coupled Model Intercomparison Project (CMIP5; Taylor, 2012) exhibit no consensus on projected change. A recent study of 10 CMIP5 models revealed projected precipitation change in the Blue Nile headwaters ranged from an increase of almost 40 % by the mid 21st century relative to late 20th century to a decrease of approximately 40 % at the same time period (Bhattacharjee and Zaitchik, 2014). Interestingly, some of the models with the most widely diverging projections demonstrate reasonably good representation of current climate patterns and variability for commonly used model evaluation metrics (Bhattacharjee and Zaitchik, 2014). This range of uncertainty is evident in previous multimodel comparison studies as well, as past analysis have found 21st century change in Upper Blue Nile basin flows ranging from 133 to −35 % and precipitation ranging from 55 to −9 % (Yates and Strzepek, 1998). Other studies of selected GCMs have found a smaller range of uncertainty, but no consensus on direction of change: Elshamy et al. (2008) examined 17 selected GCM's for the period 2081–2098 and found flow changes ranging from −15 to 14 %, while Nawaz et al. (2010), analyzed the output of three GCM's and deduced that the mean annual Blue Nile runoff would change by +15, 1 or −9 % by the year 2025. Analysis conducted by Taye et al. (2010) projected future climate scenarios and ran them through two hydrologic models for two catchments representing source regions of the Blue and White Nile. Results illustrated a large range in the projected flows from the baseline for both basins. Changes in projected mean annual flows from the Blue Nile catchment range from approximately −80 to 70 %.

In addition to climate change, proposed infrastructure projects will drastically alter the nature of downstream flows. There are currently no large structures along the main stem of the Blue Nile in Ethiopia, but the western portion of Ethiopia holds tremendous hydro-electric potential (Guariso et al., 1987). The Ethiopian government has had plans to increase utilization of this energy source since at least 50 years ago, when the concept of a cascade of hydroelectric dams on the Blue Nile was first proposed (Bureau of Reclamation, 1964; Guariso et al., 1987). The concept of a cascade of dams is still of interest to Ethiopia, but at present the country's development energies are focused on construction of the Grand Ethiopian Renaissance dam (GERD), located at the border with Sudan (Fig. 1). The GERD will be the Largest dam in Africa, holding back more than 60 billion cubic meters of water, and is expected to generate more than 5000 MW of electricity (Hammond, 2013). The construction of this dam will affect many aspects of water sharing in the region and raises numerous questions about its effects on downstream riparian nations.

Sudan has two large dams along the Blue Nile reach, at Roseires and Sennar. Roseries was constructed in 1966 (Chesworth et al., 1990) with a capacity to generate 280 MW of electricity. Recent construction heightened the dam and increased the reservoir volume from 3.3 bcm to more than 7 bcm (McCartney et al., 2009). The

Sennar dam was constructed in 1925 and holds back 900 million cubic meters of water (McCartney et al., 2009). Both dams were constructed to regulate flows that feed into multiple irrigation schemes, among them is the 800 000 ha (ha) Geziera scheme. The Gezeria was constructed by the Governing British magistrate in 1925 as the largest single irrigation scheme in the world at the time (Bernal, 1997). The dams also supply various schemes in Rahad, Suki as well as upstream and downstream of Sennar (McCartney et al., 2009). The Merowe dam (Fig. 1) is located further downstream, in the cataracts of the main stem Nile in northern Sudan. This is a highly arid area and the dam's primary purpose is hydropower rather than irrigation. It was constructed in 2009 and now supplies the majority of Sudan's hydroelectric power.

All discussions of Nile flow and water resource development take place on the background of a complex and lengthy history of colonial and post-colonial era negotiations (Swain, 1997). The most recent legally binding treaty involving Sudan is the 1959 Nile Water Agreement, under which Sudan and Egypt agreed to divide the average flow of 84 bcm at the old Aswan dam between the two countries: 55.5 bcm to Egypt, 10 bcm to evaporation losses, and 18.5 bcm to Sudan. The treaty also granted Sudan permission to build a dam at Roseries. The agreement was limited to the two downstream nations and does not include any upstream riparian countries, and for this reason it is generally not recognized by the other countries on the Nile. Nevertheless, as it is the most recent existing treaty and as Sudan has never disputed it, we take 18.5 bcm to be the maximum allowed water withdrawal for Sudan (see irrigation constraints).

1.2 Hydro-economic modeling in the Nile basin

Hydro-economic models integrate natural hydrologic dynamics, human infrastructure, and management options in a framework of economic costs and benefits. They are particularly valued in complex water management problems because they can inform a dynamic analysis of water resources and needs that guides basin managers and stakeholders towards an economically optimal management strategy in place of traditional, static systems based on water rights and fixed allocations (Harou et al., 2009).

The core structure of most river basin hydro-economic models is roughly similar: flows pass through a network of rivers and canals (or aquifers) and encounter nodes that represent resource infrastructure, such as reservoirs, abstraction sites, hydroelectric facilities, etc. But there is considerable diversity in the conceptual approach (simulation vs. optimization), representation of time (deterministic, stochastic, or dynamic), manner in which submodels are integrated to the hydroeconomic solution (modular vs. holistic), and, for optimization models, in the optimization objective function and algorithm (Harou et al., 2009).

Not surprisingly, the Nile River basin has been a common and important target for hydro-economic analyses. One relatively early effort was reported in Guariso et al. (1987), in which a linear optimization model was implemented to evaluate the effect of the long-discussed cascade of hydroelectric dams on the Ethiopian Blue Nile on overall benefit and on water economics in Sudan and Egypt. The optimization objectives of this model were to maximize hydropower production in Egypt, Sudan and Ethiopia, as well as downstream agricultural water supply. Simulations indicated that there was minimal tradeoff between the two competing objectives. Thus, Ethiopia's increased hydropower output would have a minor adverse effect on downstream riparian nations, but upstream flow regulation also had benefits for downstream riparian nations, including the fact that an increase in upstream flow regulation would decrease water levels in the highly evaporative downstream reservoirs, thus increasing total water availability for downstream riparian nations. This finding has been confirmed by subsequent modeling studies (e.g., Blackmore and Whittington, 2008) and plays a role in studies that investigate the benefits of cooperation in the basin (Whittington, 2004).

Another influential and relatively early optimization model for the Nile is the Nile Decision Support Tool (DST) which was developed by the Georgia Water Resources Institute. This model performs a basin wide hydrological and hydraulic simulation along with reservoir optimization capabilities and scenario assessment (Yao and Gerogakakos, 2007). The optimization model in DST utilizes the extended linear quadratic Gaussian (ELQG) control method in order to perform a stochastic multi-criteria optimization that aims to find the optimal reservoir operation (Georgakakos, 1987, 1989). A more recent basin-wide hydro-economic optimization model, the Nile Economic Optimization Model (NEOM), was presented by Whittington et al. (2005) using GAMS software. This model was used to assess the economic implications of various infrastructural developments within the basin and aims to maximize for basin wide economic benefits due to irrigation and hydropower production. The authors quantify the economic benefit of cooperation by comparing the total benefits calculated from current allocation, with the total benefits derived from full communication and cooperation between various riparian nation states. They found that cumulative economic benefits for all players more than double the realized total benefit from USD 4.1 billion in the status quo scenario to more than USD 9 billion when all nations are fully cooperating.

Other recent modeling efforts have focused on a subset of the basin and investigated problems of dynamic and transient system management. In the Eastern Nile, Goor et al. (2010) present a dynamic reservoir optimization model that employs a Stochastic Dual Optimization Program (SDDP). The model produces distribution functions for dam geometry, evaporation loss and irrigation intended to inform dam management policies (Goor et al., 2010). Block and Strzepek (2010) focus on the Ethiopian Blue Nile, implementing an Investment Model for Planning Ethiopian Nile Development (IMPEND) that calculates the economic benefit of development and changes to the climate to upstream portions of the Blue Nile. IMPEND has the ability to model the transient filling stages of the dams, as well as the stochastic nature of the climate variables, allowing for a focus on the transient nature of the development process, an aspect of water management that is absent from most other hydroeconomic models of the basin. Block and Strzepek (2010, 2012) apply the model to climate change analysis and find that the omission of this transient period in models result in the overestimation of total net benefits by more than USD 6 billion, as well as a significant change in the benefit to cost ratio of the project. Block and Strzepek (2010) also highlight changes in the hydrology that are neglected in models with no filling process: reservoir filling scenarios require that up to 170 % more water be retained in Ethiopia over 30 years compared to scenarios where the reservoirs are assumed to already be filled.

The Sudan Hydro-economic Optimization Model (SHOM) presented in this paper is intended to provide a complementary perspective on optimal water resource decision-making in the Eastern Nile. In contrast to earlier modeling efforts, we focus specifically on the Sudanese portion of the Blue Nile and the main stem Nile north of Khartoum. We do this because Sudan is a relatively understudied and a pivotal player in Nile water resource management. In addition, we use a non-linear optimization algorithm (see Sect. 2) that maximizes economic benefits and assesses trade-offs between hydropower production and irrigation within Sudan.

2 Methods

2.1 The SHOM optimization model

The General Algebraic Modeling System (GAMS) is front-end software that can be used to solve non-linear multi-objective optimization problems by calling various solvers. By using the reduced gradient method in the CONOPT algorithm, the model seeks a stationary point whilst reducing the number of variables by conducting a variable selection processes. By curtailing the number of variables and linearizing the non-linear constraints via a Taylor series approximation, the algorithm simplifies the problem and solves for the non-linear objective (Drud, 1992).

SHOM runs on monthly time steps. In this implementation the simulation network includes 2 dams located on the Blue Nile reach (Roseires and Sennar), 1 dam on the main stem Nile (Merowe), and agriculture is represented by 5 irrigation schemes corresponding to existing developments along the Blue Nile (Fig. 2). The combined storage volume of all dams is approximately 20 bcm, and the total irrigable area is 1.4 million ha. Tables 1 and 2 define all the parameters and variables in SHOM.

2.1.1 Objective function

The objective function of SHOM consists of two objectives which it seeks to maximize: agricultural and hydropower net benefits. Benefits refer to the total economic value attributed to each respective year summed over the twenty year run period. As noted by Whittington et al. (2005), the meaning of “value” takes more than one form. In this paper, the total net benefit attributed to the economic value of water is defined by the objective function and incorporates the benefits at each site location. Thus the total value of water is seen from the perspective of the producer (the State) and not from the perspective of the consumer. The objective function, illustrated below Eq. (1), represents the economic benefits from the agricultural and hydropower sectors. The total benefit attributed to hydropower production assumes infinite demand and is calculated as the total hydropower produced times the price per kilowatt hour. Initial dam infrastructural cost, cost of energy transmission and cost of dredging are not included in the objective function. Furthermore it is assumed in the sensitivity analysis presented in this paper that the price of electricity is fixed. Thus:

$$\text{Objective} = \max \sum_{\mathrm{l,m,y}} \left(D^{y} \times \mathrm{AGM} \times I_{\mathrm{l,m,y}} + D^{y} \times P_{\mathrm{l,m,y}} \mathrm{KWH}_{\mathrm{l,m,y}} \right) \tag{1}$$

where AGM = AGricultural profit Margin (see sensitivity parameter section), D^{y} = discount rate, $I_{\mathrm{l,m,y}}$ is the total benefits from Irrigation, $P_{\mathrm{l,m,y}}$ is the fixed price of energy per KWH, and all variables are dependent on location (“l”), month (“m”) and year (“y”).

2.1.2 Hydropower constraints

Total hydropower generation ($\mathrm{KWH}_{\mathrm{l,m,y}}$) is dependent on two variable (Eq. 2), the amount of water passing through the turbines at any given time step ($\mathrm{rhe}_{\mathrm{l,m,y}}$), and the total height of water in the dam that forces water through the turbines ($h_{\mathrm{l,m,y}}$) (Cohon, 2003; Loucks et al., 1981).

$$\forall_{\mathrm{l,m,y}}, \mathrm{KWH}_{\mathrm{l,m,y}} = \frac{\mathrm{effh} \times \mathrm{rhe}_{\mathrm{l,m,y}} h_{\mathrm{l,m,y}} (\mathrm{s\,month}^{-1})}{3600} \tag{2}$$

Production of hydropower is constrained by the dam's generation capacity, thus any additional release is categorized by the model as non-hydropower release. effh is the efficiency of the dams, which was assumed to be 0.5 in the model.

2.1.3 Irrigation constraints

Irrigation production in the model is defined by a crop price and a crop yield value that is held constant throughout the length of the model run (Cohon, 2003). Values of crop price and yield were drawn from a World Bank report and the Food and Agricultural Organization (FAO) database (Plusquellec, 1990; Ghezae, 1998; FAO, 2013). The crop yield (Y_c) and crop price (P_c) are assumed to be fixed while the area irrigated ($\mathrm{Area}_{\mathrm{c,l,m,y}}$) fluctuates annually but remains constant during the cropping season Eq. (3). Therefore,

$$\forall_{\mathrm{l,m,y}}, I_{\mathrm{l,m,y}} = \sum_{\mathrm{c}} (P_\mathrm{c} Y_\mathrm{c} \mathrm{Area}_{\mathrm{c,l,m,y}}) \tag{3}$$

The model maximizes $I_{\mathrm{l,m,y}}$ and derives the area irrigated during the cropping season ($\mathrm{Area}_{\mathrm{c,l,m,y}}$) thus determining the amount of water allocated for irrigation ($i_{\mathrm{l,m,y}}$). $i_{\mathrm{l,m,y}}$ is dependent on the water content for each crop type, at a specific month in a particular year Eq. (4). Efficiency of irrigation was assumed to be 80 % for all irrigation schemes. (NB: the agricultural output in the objective function is irrigation fed; rain-fed agriculture was not considered. Also, effi = 1.25, and is the inverse of the irrigation efficiency. A larger efficiency requires less water and a lower $i_{\mathrm{l,m,y}}$.)

$$i_{\mathrm{l,m,y}} = \sum_{\mathrm{c}} (\mathrm{effi} \times \mathrm{Water}_{\mathrm{c,l,m,y}} \times \mathrm{Area}_{\mathrm{c,l,m,y}}) \tag{4}$$

Finally, per the 1959 Nile agreement Sudan's portion of withdrawals is limited to 18.5 bcm of water annually Eq. (5). Thus for a simulation of Y years the total water consumed by Sudan should be:

$$\sum_{\mathrm{l,m,y}} (i_{\mathrm{l,m,y}}) \leq Y \times 18.5\,\mathrm{bcm} \tag{5}$$

This constraint should, formally, be applied to the entire Nile network within Sudan rather than just to the Blue Nile and main stem Nile, and there is certainly some water consumed in reservoirs and irrigation on the White Nile south of Khartoum and in the other Eastern Nile tributaries. However, the Blue Nile represents the majority of water flow and usable water resource, and all of the largest irrigation schemes in Sudan lie within the Blue Nile basin (Knott and Hewitt, 1994). So we allow the model to use up to the full 18.5 bcm year^{-1} constraint as a generous but not terribly unrealistic constraint.

2.1.4 Continuity constraints

The storage at each dam location must be equal to a simple water balance. The storage at a particular time step is the total water contained in the dam in the previous time step plus the water entering each dam minus what comes out of the dam through upstream flow Eq. (6). The water entering is the upstream boundary flow or upstream total dam release ($q_{\mathrm{l,m,y}}$ or $r_{\mathrm{l,m,y}}$ respectively), the water leaving each dam node is the current dam release, the irrigated water and water loss due to evaporation.

$$\forall_{\mathrm{l,m,y}}, s_{\mathrm{l,m,y}} = q_{\mathrm{l,m,y}} + r_{(l-1),\mathrm{m,y}} + s_{\mathrm{l,(m-1),y}} - r_{\mathrm{l,m,y}} - i_{\mathrm{l,m,y}} - e_{\mathrm{l,m,y}} \tag{6}$$

NB: $s_{\mathrm{l,(m-1),y}}$ is the storage from the previous time step. When $m = 1$, the model uses the storage from $s_{\mathrm{l,12,(y-1)}}$. Evaporation in m^3 m^{-2} (Ev) is estimated using the Thornthwaite equation (Thornthwaite, 1948), thus the total evaporated volume: e = Ev × Dam Surface Area. The storage at each time step must also be less than each dam's respective maximum volume ($V_{\max}$) Eq. (7).

$$s_{l,m,y} \leq V_{\max} \tag{7}$$

Lastly all the decision variables calculated by the optimization model must satisfy non-negativity constraints (Eq. 8)

$$\text{i.e.: } s_{l,m,y}, \text{rhe}_{l,m,y}, i_{l,m,y} \geq 0. \tag{8}$$

2.2 Model parameters

2.2.1 Agricultural Profit Margin (AGM)

Deriving the net benefits due to agriculture requires an intimate knowledge of both foreign and domestic agricultural economic markets. Calculating prices of output commodities relative to input production costs for future scenarios would require accurate price prediction of a non-linear, volatile market. Rather than attempt to analyze and project costs of agricultural inputs (e.g., water rates, fertilizer, land and labor) or to simplify tax rules and subsidies currently affecting agricultural prices in Sudan, we have simply defined an "agricultural profit margin" (AGM) that represents the nation state's fractional social benefit of agricultural production. The net benefit of agriculture is calculated by multiplying the total benefits (crop price × total production in irrigated lands) by the AGM factor. To explore the sensitivities of the model to agricultural production this AGM functions as an objective weight and is varied within the objective function to develop a tradeoff between the various objectives, as described in Sect. 3.

2.2.2 Discount rate (D^y)

Economic analyses of large-scale development projects need to assign a discount rate to discount anticipated future benefits relative to near-term costs and benefits forgone. Since the objective function and decision making in our model is solely based on economics, the discount rate can greatly influence the final value of the objective function of the model. To quantify this influence we performed simulations in which discount rate was varied from 3 to 7 %, a range that has a considerable impact on the total value of the objective function. The same discount rate was applied to both objectives within the objective function. The results presented in Sect. 3 used a discount rate of 5 % for all analyses.

2.2.3 Flows

As noted above, there is significant uncertainty in projections of future precipitation patterns – and hence future river flows – in the Blue Nile basin. For this reason we consider it important to test model sensitivity to substantial increases (+20 %) and decreases (–20 %) in river flow, which is within the range of predictions of state of the art global climate models for the first half of the 21st century.

In addition, we are interested in how the model responds to temporal smoothing of inflow from Ethiopia, as might result from the construction of one or more upstream dams. For this reason we include a third flow scenario in which the annual total flow is unchanged from present conditions but monthly flow values are averaged across three months, producing a smoothed hydrograph with less extreme wet season peaks and dry season troughs.

Increases and decreases in flows were restricted to the Blue Nile flows only; White Nile flows remained unchanged. This approach was adopted for multiple reasons. First, the White Nile originates in the Equatorial Lakes region, which is in a different climate zone. Thus it is unclear that an increase in Blue Nile flows would translate into an increase in White Nile flows. Second, the White Nile passes through the Equatorial lakes and Sudd wetland, so that its annual flow is more buffered than the Blue Nile. Lastly, majority of the water in Egypt originates from the Blue Nile region, so changes in White Nile flow under climate change would not impact the main stem Nile as significantly as changes in the Blue Nile.

2.2.4 Bootstrapped flows

All simulations in the sensitivity analysis were run for 20 years. To generate hydrological inputs for these simulations a 70 year record of monthly observed Blue Nile flows at Roseires was obtained from the Global Runoff Data Center (www.grdc.org). This record was randomly resampled to generate 1000 20 year timeseries of representative flow patterns. The mean flow for all 1000 timeseries were assembled and ranked, thus defining the 5 and 95 % confidence levels of flows for the 20 year observed period. The model output was assessed using these confidence intervals.

3 Results and discussions

3.1 Model behavior

To demonstrate general model behavior we first examine a 20 year demonstration simulation that uses bootstrapped historical flows and a moderate AGM of 0.12. Hydrologic fluxes and storages at the three dams in the simulation (Roseires, Sennar, and Merowe) and for major irrigation areas are shown in Figs. 3 and 4.

Figure 3a shows the observed 20 year flows for the Blue Nile at the Sudan–Ethiopia border. Fluctuations of flows are illustrative of the wet and dry seasonal pattern, showing significant intraseasonal variability. Annual flows for this record also vary significantly, from −26 to 26 % of the mean, indicative of a substantial inter-annual variability. This record shows two distinct periods of below average annual flows (months 70–120 and months 190–240). The dam storage and release values reflect a response by the model to these periods of interseasonal dryness and wetness. The smaller dams (Roseries and Sennar) are emptied and filled annually (Fig. 3b) with Merowe remaining relatively full year round in all years, with minor drops in its storage level during the dry months. Therefore there is no significant connection between the hydropower releases at Merowe and inter-annual variability. There is a significant connection between dry periods and hydropower release at Roseries. This is illustrated by a reduction in Hydropower release during the periods of dry annual flows (months 70–120 and months 190–240), and higher hydropower release during wet periods (Fig. 3c).

Figure 4 also shows results for the base case simulation, but as 20 year average seasonal cycles of storage, release, and withdrawals at each major dam and irrigation zone across the 1000 bootstrapped simulations. It is clear from Fig. 4a that the large reservoir at Merowe is relatively insensitive to seasonal variability and to climatic variability represented by bootstrapping. This offers a more robust view of the sensitivity of optimal reservoir operation and water withdrawals to season and to potential patterns of variability given historical conditions.

Figure 4a shows that the dams along the Blue Nile (Sennar and Roseires), in contrast, are significantly sensitive to seasonal and interannual variability: in the months preceding the wet season both Sennar and Roseires are emptied and then refilled during the rainy season, while Merowe is able to remain relatively full year round maximizing hydropower generation. This is in small part a product of the fact that Blue Nile flows are more strongly seasonal than main stem flows, which are slightly moderated by inflow from the White Nile. But the primary reason for the difference is the model's objective to maximize total benefit through the system. Maximizing hydropower output requires large hydropower release (Fig. 4b), and adequate head through the turbines (see hydropower constraints section). Since Merowe is the largest hydroelectric facility, it is critical to hydropower optimization that it is active and that its reservoir is relatively full for as much of the year as possible. The model maximizes hydropower by maintain Merowe at full capacity for most of the dry months at the expense of the storage at Roseries and Sennar. Thus Roseries is emptied between January to May and a relatively full dam is maintained at Merowe for most of the dry season, maximizing total hydropower production. Since the Blue Nile has highly seasonal flows and Roseires and Sennar are relatively small dams, this comes at the cost of seasonally reduced reservoir storage and hydropower potential at those dams. In Fig. 4a and b, the largest variability between simulations (biggest ± bars) is observed during the months of emptying and filling (February–August), reflecting sensitivity to inter-annual climate variability.

Figure 4c shows total water withdrawal amounts during the cropping season upstream of Sennar dam, which would include the Rahad, Suki and Upstream Sennar irrigation schemes, and upstream of Merowe dam, which includes the Geziera and Downstream Sennar irrigation schemes. Since the larger schemes are situated upstream of Merowe and downstream of Sennar, the largest withdrawals are downstream of Sennar. There were four crops modeled with different cropping cycles that overlapped during the season (Table 1), so the total agricultural water requirement varied on a monthly basis. Withdrawals, however, were maintained at between 2–3 bcm on average from July to January and drop to zero during the February to June non-cropping period.

Currently, the influence of agriculture on dam management is limited due to two factors. First, though the crop calendar is somewhat different for each of the four crops, there is only one cropping season, which approximately coincides with the wet months, so agricultural productivity peaks when the water supply via Blue Nile peak flows is plentiful (Fig. 4c) and the total annual withdrawals are limited by prevailing agricultural practices. Second, as shown in the tradeoff analysis below (Sect. 3.2), the 18.5 bcm year^{-1} maximum withdrawal stipulated in the 1959 Nile Waters Agreement serves as a cap on water withdrawals in high AGM scenarios that would otherwise favor larger agricultural production.

3.2 Tradeoff analysis

Understanding the tradeoff between hydropower and irrigation is central to understanding how the model allocates water to the different objectives. Figure 5 shows results of simulations in which the AGM factor is maintained at a constant value while the unit benefit of hydropower is varied, for historical flow conditions. The agricultural benefit is removed from the objective function and phrased as a constraint, and thus a tradeoff curve can be constructed that illustrates the hydropower–agriculture relationship for that specific AGM. For high AGM (e.g., AGM = 0.4), the gradient of the tradeoff curve is low. Thus the loss of one unit benefit of hydropower would result in a gain of more than one unit benefit of irrigation. In order to maximize total benefits, then, the model would allocate more and more water to agricultural production until it hits a constraint. For low AGM (e.g., AGM = 0.1) the opposite is true: the model prioritizes moving water through the turbines at the expense of agriculture. For intermediate AGM (e.g., AGM = 0.16) there is an inflection point at which the gradient is equal to 1.0 (circled point in Fig. 5). To the left of the point the gradient is less than 1.0, which would cause the model to shift towards agriculture, and to the right it is greater than 1.0, pushing the model back towards hydropower. Thus the inflection point is the optimum balance between agriculture and hydropower for that AGM under given simulation conditions.

The implications of the optimal inflection point for total benefits are illustrated schematically in Fig. 6. The blue line in Fig. 6 represents a base case scenario with an optimum division between irrigation and hydropower indicated by the inflection point at gradient equal to one. The other lines are representative of scenarios in which changing conditions – altered flow regime, market modifications, policy decisions, or other external factors – shift the optimum in a manner that can change both the total value realized from the system and the division between irrigation and hydropower. A movement up and to the right on the chart is a win-win condition for Sudan in which both irrigation and hydropower benefits increase, while a move down and to the left is a lose-lose scenario. Movement up and to the left and down and to the right are trade-off scenarios in which hydropower benefit increases to the detriment of irrigation and vice versa. The interpretation of these “wins” and “losses” would, of course, differ for other stakeholders. Egypt might view movement to the right on the chart – increasing irrigation withdrawals – as a potential threat to water resources in the absence increased Nile river flow or counterbalancing shared benefits.

With this framework in mind, we next consider simulations in which flow scenarios are added to the analysis while maintaining a constant AGM value. These simulations allow us to ascertain the changing nature of the tradeoff curves for changes in mean flow consistent with the range of predicted climate change and for changes in flow timing representative of flow regulation from upstream development. A value of AGM = 0.12 is used because it represents an intermediate profitability value; AGM greater than 0.14 was found to push some scenarios up to the 18.5 bcm constraint while AGM less than 0.1 pushed simulations strongly towards hydropower. Figure 7 shows the results of these scenarios, with inflection points indicated as circles around the point at which the gradient crosses through 1.0. These circled data points are the optimal values for each scenario at which the model would converge for the given hydrologic inputs and parameter values.

The relative position of these inflection points lies at the core of optimization-based hydro-economic analysis. When a change in hydrology (e.g., "smooth flow" vs. "observed flow") causes the inflection point to move to the right on the chart it suggests that this hydrologic change will push Sudan towards more irrigation. Similarly, if the inflection point moves up on the chart it suggests that the hydrologic change is pushing Sudan towards hydropower. These dynamics matter enormously for studies of how climate change or upstream development is likely to impact Sudan's water resource decision-making. Movement that is up and to the left or down and to the right is particularly interesting, as it suggests that Sudan's optimal development strategy involves a shift between hydropower and irrigation. In more general terms, a hydrologic shift that moves the optimal point up and to the left on Fig. 6 could be thought of as a change that pushes Sudan towards a hydropower development pathway, while a shift that moves the point down and to the right pushes Sudan towards an irrigation development pathway relative to baseline simulation conditions.

For this fixed AGM analysis, model sensitivity to reduced flow (–20 %) is consistent with expectation. A low flow scenario at AGM = 0.12 results in a dramatic decrease in benefits from irrigation and a slight decrease in hydropower production (triangles and dashed line in Fig. 7). Interestingly, sensitivity to increased flow (+20 %) is not as intuitive: increased flow concentrated over the wet months would significantly increase agricultural production at the expense of downstream hydropower production, thus leading to a slight decrease in hydropower but a total increase in the overall objective function (squares and dotted line in Fig. 7). Lastly, the smoothed flows show an increase in hydropower and irrigation benefits. Stabilized flows increase water availability during the dry season and at the tail ends of the wet season, and thus there is more water available throughout the year for irrigation and hydropower, increasing the benefits to both (x's and solid line in Fig. 7).

Next, the sensitivity to agricultural value was analyzed by changing the AGM factor. Figure 8 shows the trade-off curve of Pareto optimal values of hydropower and irrigation benefits for AGM ranging from 0.08 to 0.22. A solution point is Pareto optimal if there is no other feasible point that improves at least one objective function without exacerbating another objective function. As described above, a higher AGM assigns greater weight to agricultural production, which could be interpreted as a higher agricultural profit margin or as a higher perceived value of agricultural activity by policy makers. First, we note that for all scenarios in Fig. 8 the tradeoff curves flatten out at very high values of irrigation benefit. This flattening reflects the fact that at high AGM the model is withdrawing near the maximum amount of water allowed under the 18.5 bcm constraint imposed by the 1959 Nile Waters Agreement. The trade-off curve approaches horizontal because the same amount of water is allowed to pass downstream through the turbines at Merowe while the calculated irrigation benefit per unit water continues to increase when AGM is set to higher and higher values.

Perhaps more interesting, Fig. 8 can also be used to study how AGM affects the impact that a change in flow regime has on optimal water allocation. For example, the circles in Fig. 8 highlight the same optimal points indicated by the circles in Fig. 7 – i.e., the inflection points for each scenario when AGM is set at 0.12. The boxes in Fig. 8 indicate the same inflection points but for a case of AGM equal to 0.16. For AGM = 0.12 a scenario of smoothed flow (upstream development) provides a win-win for Sudan: greater irrigation benefits and slightly higher hydropower benefits. But for AGM = 0.16 smoothed flow pushes back against irrigation use: there is an increase in hydropower benefit and in total benefit, but a decrease in water used for irrigation.

In other words, smoothed flows allow for more effective use of existing hydropower infrastructure and this pushes against the high irrigation allocations in the baseline AGM = 0.16 simulation, driving Sudan towards hydropower.

While this result is somewhat understandable – the high AGM means that Sudan still has large irrigation in the smoothed AGM = 0.16 simulation relative to the AGM = 0.12 scenario, so a rebalancing towards hydropower isn't entirely unrealistic – it ignores the fact that a large upstream facility regulating Blue Nile flow would almost certainly produce a large amount of hydropower itself, and in an connected electricity market this would drive down the price of electricity. The GERD, for example, is expected to generate electricity that can be sold at about half the price of existing Sudanese facilities, and the dam will be connected to the Sudanese grid. To account for this dynamic in general terms, we include another model simulation in which flow is smoothed and the price of electricity is cut from 12 to 6 cents KWh^{-1} – a "SmoothPower" scenario. As shown in Fig. 8, this drop in the price of power will result in a shift in policy from a hydropower-centric solution to a policy that increases agricultural production. For all AGM, the SmoothPower curve data points show greater irrigation benefits.

We note that all of these results, including the shift to agriculture in SmoothPower, are for existing cropping practices. In reality, upstream development will increase water availability during the dry months, which will incentivize farmers to change their agricultural practices. This has already been observed on the Atbara River, just north of the Blue Nile, where construction of a dam in Ethiopia has led Sudanese farmers to transition from a one cropping season to a multiple cropping season and to diversify crop types. This suggests that our model underestimates the total irrigation potential under upstream development scenarios because we do not include the potential for large-scale changes in agricultural practice. This would be particularly true for scenarios with low AGM where the 18.5 bcm constraint is not met. Methods to include a broader range of crop and seasonality options in the optimization modeling framework are the subject of ongoing research.

4 Conclusions

This paper introduces a hydroeconomic model for Sudan (SHOM) that considers hydropower and irrigation benefits under conditions of existing infrastructure and practices. SHOM includes a nonlinear multiobjective optimization routine that allows us to study interactions between component objectives under a range of flow scenarios and valuation of agricultural returns. A number of our modeling results confirm or complement previous hydro-economic analyses – for example, the fact that upstream regulation can provide benefits to downstream riparians. Other results are intuitive, such as the fact that under reduced flows there is a decline in hydropower and irrigation benefits. However, even in this simple sensitivity test the model returns some non-obvious results. While one might expect that smoothing the Blue Nile hydrograph through upstream regulation would lead to increased irrigation withdrawals, we find that this is only true if the upstream facility results in a drop in the price of electricity in Sudan. Otherwise the optimal development path is to increase hydropower production, while the decision on whether to increase or decrease irrigation depends on the agricultural margin and/or to the ability of Sudan to shift prevailing agricultural practices beyond the existing cropping seasons included in our model.

Another interesting result is that when the price of electricity is cut in half Sudan shifts towards an irrigation development path. This is clear in our modeling results (Fig. 8) and is almost certainly an underestimate of the push towards irrigation since we are not considering large-scale changes in agricultural practices. The more that economic considerations push Sudan towards irrigation, the more expensive the 1959 Nile Waters Agreement becomes to the country. The requirement to use no more than 18.5 bcm year^{-1} is not a severe constraint as long as agriculture is economically inefficient, irrigation is hampered by siltation and seasonal flow variability, and hydropower is an economic driver to send water downstream. But if these realities are shifted by an upstream facility that regulates flow, reduces sediment load, and provides inexpensive electricity, the treaty-enforced cap on water use will quickly become a constraint on Sudan's optimal hydro-development options.

The modeling results presented in this study contribute to current understanding of Nile hydro-economics by presenting a focused analysis of Sudanese options, performed with a multiobjective optimization model capable of capturing nonlinear interactions. There are, however, a number of important limitations that need to be addressed in future model development. First, the model does not include knowledge of current dam operating procedures or of stage–volume relationships for proposed dams (GERD) or for existing dams in recent years. Second, the model does not include the effects of siltation. A dam that controls siltation would affect the objective function by easing dam operation and significantly reducing dredging costs for canals that feed irrigation schemes. At the same time, reduced silt load would increase the need for fertilizer in downstream agricultural lands that currently benefit from natural nutrient input from silt-laden waters. Third, limitations in current agricultural and economic data make it difficult to estimate total agricultural benefits, so AGM essentially functions as a tuning parameter in SHOM that allows us to study general sensitivity to the value of agriculture but that is not grounded in data. This could certainly be improved with access to more reliable and recent agricultural data, though the perceived value of agriculture and the support of this value through land and economic policies are always difficult to quantify.

The scope of SHOM is also a matter of ongoing evaluation. In focusing on hydropower and irrigation we adopt the framework of many earlier hydro-economic optimization models in the Nile and elsewhere. We recognize, however, that climate change and river development can have a broad range of impacts, many of which are difficult to quantify. These include ecological impacts, effects on fisheries, and burden placed on particular populations living within the basin. These important considerations must be accounted for in any application of hydro-economic analysis to development decision making, and it would be valuable to find ways to broaden Nile basin hydro-economic models to include a more diverse array of processes and outcome variables. In further development we may also include the White Nile and other Eastern Nile tributaries in the model, add in future infrastructure currently included in national development plans, and consider the emerging external influence of foreign land purchases, which are opening up new frontiers in irrigation that are subject to systematically different optimization objectives and constraints.

The Nile River is a finite water resource shared by a number of emerging economies, and the long-standing tensions regarding its equitable use are only increasing as demand for food, water, and electricity rise across the region. On account of both history (i.e., the 1959 Nile Waters Agreement) and geography, the Republic of Sudan is a particularly critical player in determining the future of Nile development and related hydro-economic development decisions in neighboring countries. The effect of climate change and upstream development, in turn, will be critically important in determining Sudan's long term optimal development path and associated policy decisions. Here we present a first analysis targeted specifically at Sudan's optimal irrigation and hydropower development options under scenarios of changing Nile flows and upstream development. Results reinforce the understanding that Sudan has the potential to weigh in heavily on matters of regional water and food security depending on how it chooses to make use of the Blue Nile and main stem Nile as it flows through its territory. Further research is required to understand how these choices are affected by additional development, trade, and policy decisions within the basin, and how Sudan's own infrastructure and agricultural practices might evolve to optimize returns under evolving climatic and economic conditions.

Appendix A: SHOM model

Objective function:

$$\max \sum_{\mathrm{l,m,y}} \left(D^y \times \mathrm{AGM} \times I_{\mathrm{l,m,y}} + D^y \times P_{\mathrm{l,m,y}} \mathrm{KWH}_{\mathrm{l,m,y}} \right) \tag{A1}$$

Constraints

Hydropower:

$$\forall_{\mathrm{l,m,y}}, \mathrm{KWH}_{\mathrm{l,m,y}} = \frac{\mathrm{effh} \times \mathrm{rhe}_{\mathrm{l,m,y}} h_{\mathrm{l,m,y}} (\mathrm{s\,month}^{-1})}{3600} \tag{A2}$$

$$\forall_{\mathrm{l,m,y}}, r_{\mathrm{l,m,y}} = \mathrm{rhe}_{\mathrm{l,m,y}} + \mathrm{nhe}_{\mathrm{l,m,y}} \tag{A3}$$

$r_{\mathrm{l,m,y}}$ = total release, $\mathrm{rhe}_{\mathrm{l,m,y}}$ = hydropower release, $\mathrm{nhe}_{\mathrm{l,m,y}}$ = non-hydropower release

$$\forall_{\mathrm{l,m,y}}, \mathrm{rhe}_{\mathrm{l,m,y}} \leq Q_{\mathrm{dc}} \tag{A4}$$

where Q_{dc} is the flow capacity through the turbines.

Irrigation:

$$\forall_{\mathrm{l,m,y}}, I_{\mathrm{l,m,y}} = \sum_{\mathrm{c}} (P_{\mathrm{c}} Y_{\mathrm{c}} \mathrm{Area}_{\mathrm{c,l,m,y}}) \tag{A5}$$

$$i_{\mathrm{l,m,y}} = \sum_{\mathrm{c}} (\mathrm{effi} \times \ \mathrm{Water}_{\mathrm{c,l,m,y}} \times \mathrm{Area}_{\mathrm{c,l,m,y}}) \tag{A6}$$

$$\sum_{\mathrm{l,m,y}} (i_{\mathrm{l,m,y}}) \leq Y \times 18.5\,\mathrm{bcm} \tag{A7}$$

$$\sum_{\mathrm{c,l}} \mathrm{Area}_{\mathrm{c,l,m,y}} \leq 1.4\,\mathrm{million\,ha} \tag{A8}$$

Continuity:

$$\forall_{\mathrm{l,m,y}}, s_{\mathrm{l,m,y}} = q_{\mathrm{l,m,y}} + r_{(\mathrm{l}-1),\mathrm{m,y}} + s_{\mathrm{l},(\mathrm{m}-1),\mathrm{y}} - r_{\mathrm{l,m,y}} - i_{\mathrm{l,m,y}} - e_{\mathrm{l,m,y}} \tag{A9}$$

$$s_{\mathrm{l,m,y}} \leq V - \max \tag{A10}$$

Non Negativity Constraints: $s_{\mathrm{l,m,y}}, \mathrm{rhe}_{\mathrm{l,m,y}}, \mathrm{nhe}_{\mathrm{l,m,y}}, r_{\mathrm{l,m,y}}, i_{\mathrm{l,m,y}}, \mathrm{Area}_{\mathrm{c,l,m,y}} \geq 0$ (A11)

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Data is available at the Global Runoff Data Center (GRDC) GRDC Station NO.16663800 and NOAA National Climate Data Center (NCDC) Global Historical Climatology Network-Monthly (GHCN-M) temperature dataset station Wad Medina nr62751 in ghcnm.tavg.v3.qcu v3.2.2.20140804, WMO Station code 62751.

(http://climexp.knmi.nl), as well as the Food and Agricultural (FAO) dataset (FAOSTAT) (http://faostat.fao.org/).

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Table 1. SHOM parameters.

Parameters	Value Range	Units	Notes
AGM	0.08–0.22	–	Agricultural profit Margin
Discount Rate (D^y)	3–7 %	–	5 % used in the simulation analysis
Flows (q)			
High	20 %	Million m^3 $month^{-1}$	CI = Confidence Intervals
Low	–20 %		
Smooth	3 month Average		
Bootstrapped Flows	5, 50, 95 % CI		
Yield (Y_c)			
Wheat	100	tons per million m^2	Plusquellec (1990),
Cotton	140		Ghezae (1998),
Sorghum	800		FAO (2013)
Groundnuts	350		
Water Requirement (Water)			
Wheat	0.23–0.48	m^3 m^{-2}	Value depends on Month
Cotton	0.48–0.73		Plusquellec (1990),
Sorghum	0.69–0.94		Ghezae (1998)
Groundnuts	0.89–1.14		
Efficiency			
effi	1.25	–	Irrigation Efficiency
effh	0.5	–	Hydropower Efficiency
Prices (Pc)			
Wheat	199	USD t^{-1}	FAO, (2013)
Cotton	1849	USD t^{-1}	
Sorghum	125	USD t^{-1}	
Groundnuts	372	USD t^{-1}	
Power (P)	0.12	cents kWh^{-1}	
Evaporation	0.08–0.3	m^3 m^{-2}	Evaporation is derived from the Thornthwaite equation (Thornthwaite, 1948). Range Depends on Month and location.
e	1.9–76.5	Million m^3	e = Ev × Dam Surface Area

Table 2. SHOM variable definitions.

Variables	Definition	Units	Notes
s	Storage	Million $\text{m}^3\,\text{month}^{-1}$	Storage volume is assumed to be cylindrical in the model
r	Release (r = rhe + nhe)	Million $\text{m}^3\,\text{month}^{-1}$	Release has two components, rhe = Hydropower release, nhe = non-hydropower release
i	Irrigation Volume	Million $\text{m}^3\,\text{month}^{-1}$	
Area	Area Irrigated	Million $\text{m}^2\,\text{month}^{-1}$	
I	Irrigation Benefits	USD	
KWH	Power Generated	kWh	Calculated from the hydropower equation. Function of hydropower release and head

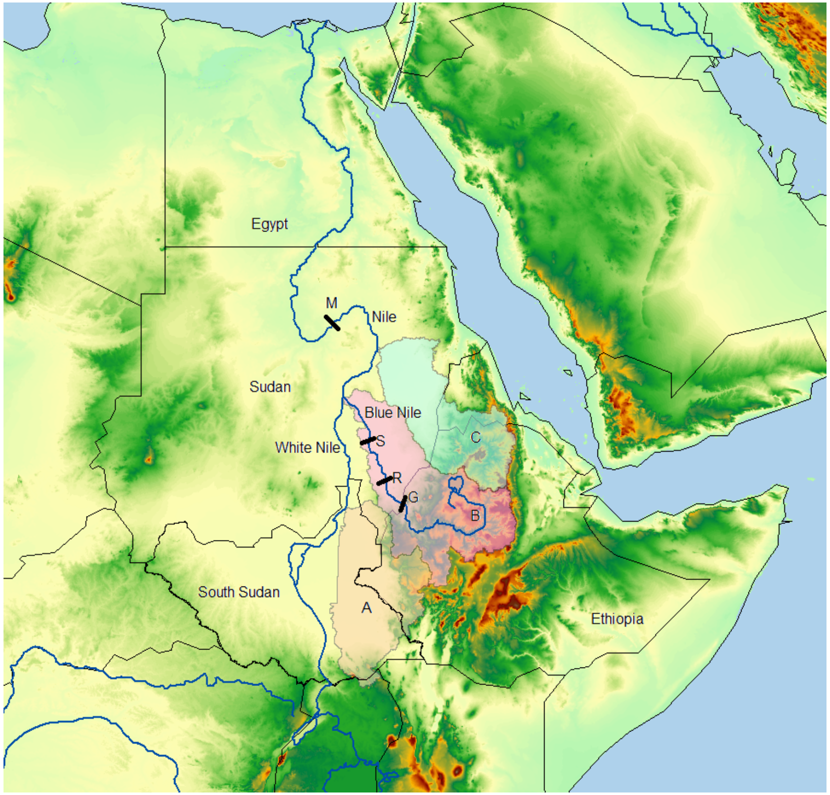

Figure 1. Map of the Nile and its tributaries A = Baro-Akobo-Sobat, B = Blue Nile, C = Tekese-Atbara Basins, S = Sennar Dam, R = Roseries Dam, M = Merowe Dam and G = GERD.

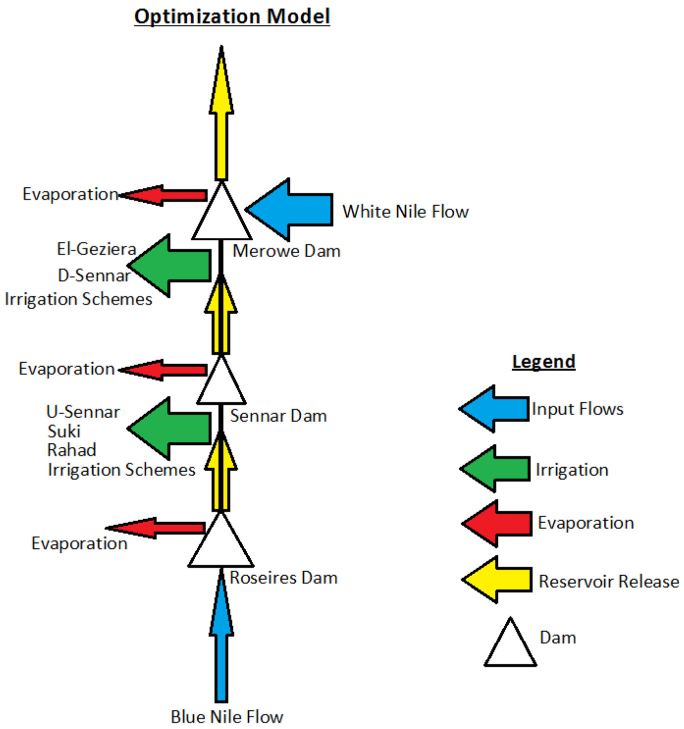

Figure 2. Schematic of the optimization model.

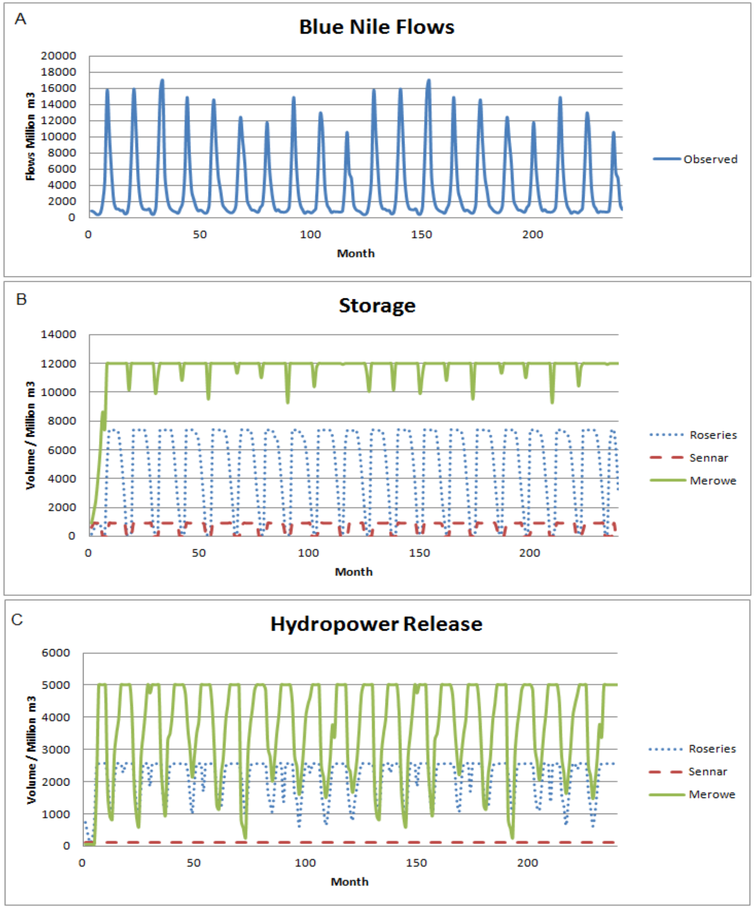

Figure 3. Annual cycle of **(a)** observed flow, **(b)** storage and **(c)** hydropower release at the three dams over the 20 year demonstration simulation.

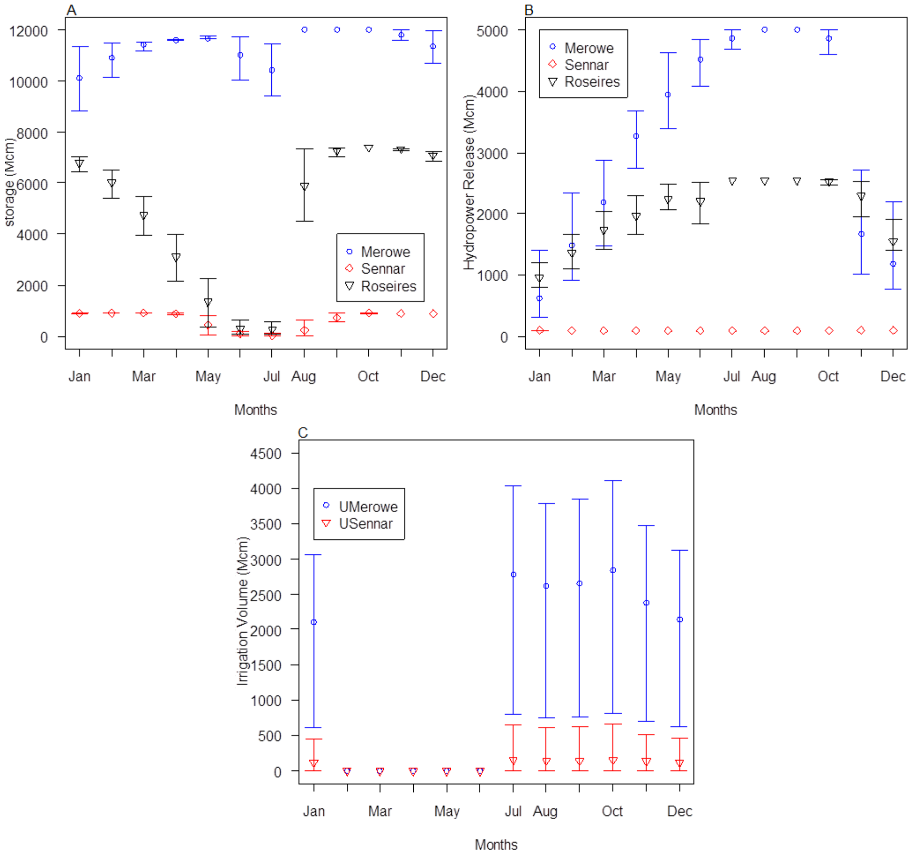

Figure 4. Annual cycle of **(a)** reservoir storage and **(b)** hydropower release at the three dams, and **(c)** irrigation withdrawals upstream of Sennar and upstream of Merowe in the base case simulation of bootstrapped historical flows and AGM = 0.12. Data points are the mean average value over the 20 year simulation and error bars represent the difference in output between the 5 and 95 % confidence interval bootstrapped flow.

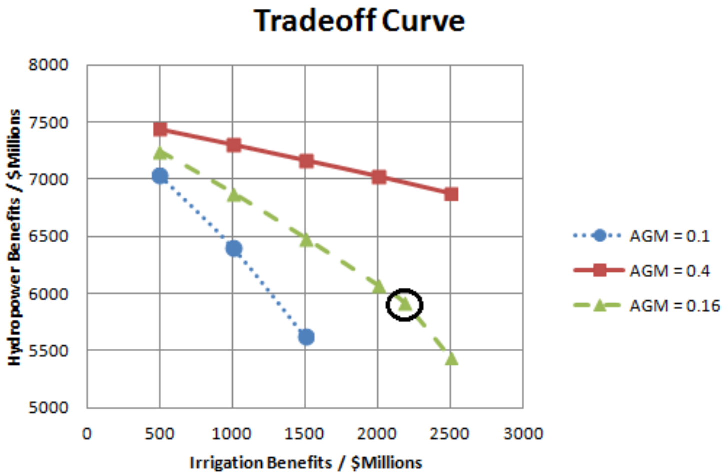

Figure 5. SHOM hydropower vs. irrigation benefit trade off curves for three different values of AGM.

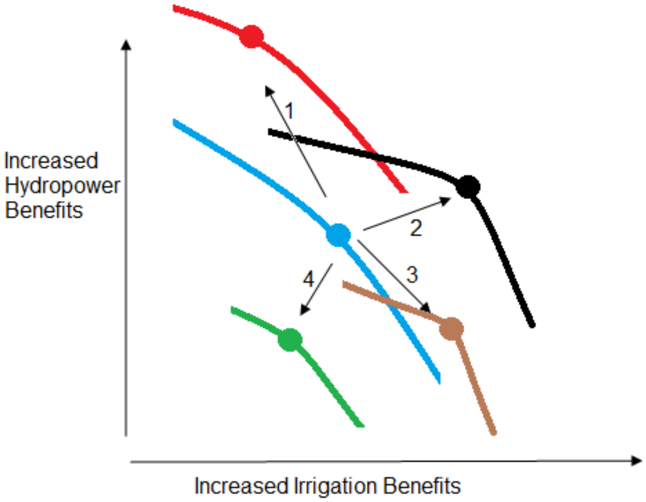

Figure 6. Schematic of the four possible ways in which changing conditions can shift the optimum model solution from a baseline set of solutions represented by the blue curve. Arrow 1 (shift to red curve) depicts a win-loss tradeoff where a loss in irrigation benefits is offset by an increased in hydropower benefits. Arrow 2 (shift to black curve) depicts a win-win outcome, with a gain in both hydropower and irrigation. Similarly, arrows 3 and 4 can be characterized as loss-win and loss-loss, respectively.

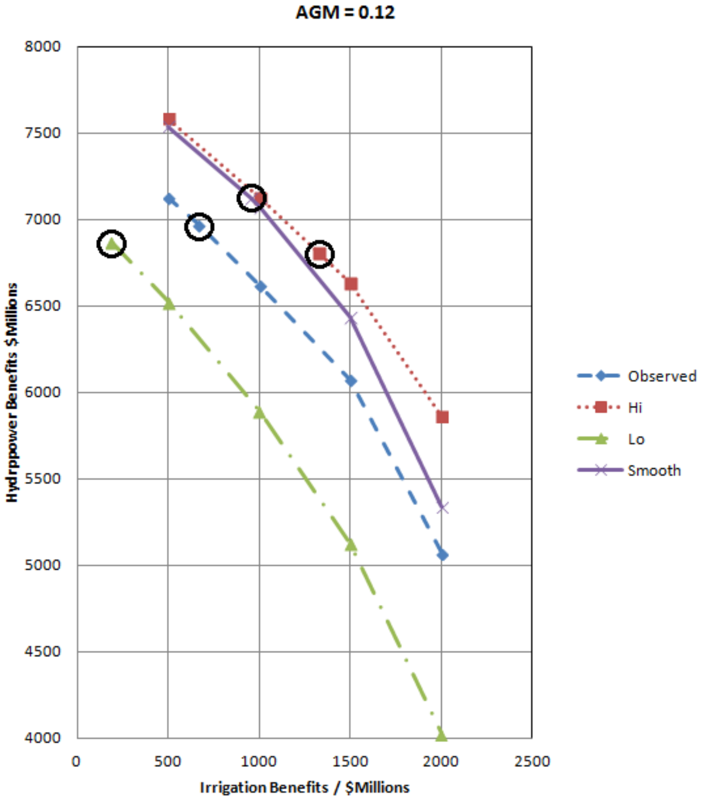

Figure 7. Results of SHOM simulations in which the agricultural benefits are phrased as constraints, and the hydropower benefits are calculated for a specific agricultural benefit. The circles highlight the optimal values for each scenario.

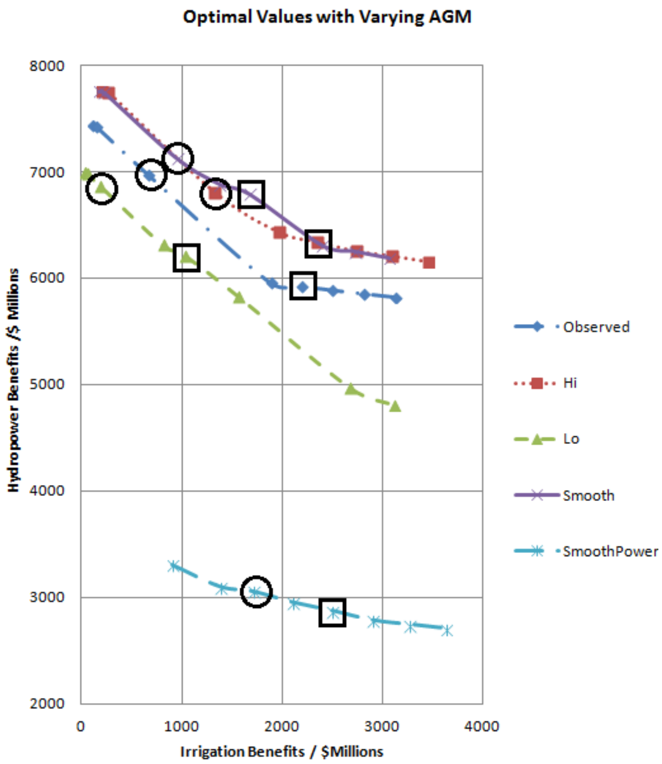

Figure 8. Hydropower vs. irrigation benefits in SHOM simulations as the AGM is increased from 0.08 to 0.22. Data points for each scenario are the Pareto optimal values with varying AGM. Data points circled are Pareto optima for AGM = 0.12 and data points highlighted with a square are Pareto optima for AGM = 0.16.