SUPPLEMENTARY INFORMATION

The role of rainfed agriculture in securing food production in the Nile Basin

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1. The WaterWise-Nile model

To study the influence of various forms of cooperation on the optimal allocation of land, water, and investments for maximum food production in the Nile Basin, the hydro-economic model WaterWise (WW) was applied. The Waterwise model code is formulated within a Mixed Integer Linear Programming framework (MILP). The model equations have been implemented in Xpress-Mosel (Fico, 2014). Model code and a more detailed description of input and output can be found at www.waterwijs.nl. In this supplement a short introduction to the model and specific details of the Nile basin application are given.

The model has the specific ability to suggest investments that make best use of the available land and water resources. It solves the problem of economic scarcity, with the implementation of local investments having consequences for the physical possibility of investments elsewhere. The primary model option is to use the total gross margin (GM) as the objective function:

$$Y_{TOT} = Y_{LU} + Y_{HP} - C_{LWM} - C_{RWM} \qquad [1]$$

where Y_{TOT} represents total GM (USD/yr), Y_{LU} the GM of land use (USD/yr), Y_{HP} the GM of hydropower (USD/yr), C_{LWM} the costs of local water-management measures for supporting land use (i.e., fixed and variable costs of local irrigation measures per hectare or per m^3 of water [USD/yr]), C_{RWM} are the costs of regional water management (i.e., maintenance costs for large canals and the costs of flow-through connections that involve pumping to support the river, canal, and reservoir system [USD/yr]). This last option was not used in the Nile Basin application.

In the typology given by (a.o) Brouwer and Hofkes (2008), hydro-economic models can be categorized into (1) compartment or modular approach (2) holistic approach that in most cases using some form of mathematical programming for performing an economic optimization. WW is an example of the holistic approach that incorporates elements of the modular approach; in terms of the mentioned typology it is a hybrid. Like most hydro-economic models, WW describes the hydrologic and crop growth processes in considerable detail, whereas the economic optimization algorithm is relatively simple. The choice of using a hybrid holistic method is based on the experience that incorporating certain processes in a 'pure' holistic approach can lead to over simplification, for instance when modelling crop growth in response to water availability.

WW has external modules on water, food and energy providing the optimization model various land use and reservoir options to choose from (section S2). These options are interconnected through the WW network of river trajectories (arcs) and nodes, to which hydrotopes are linked, areas of similar soil and meteorological characteristics within a subcatchment (Figure S2). This node-arc-area representation is more flexible and generic than the commonly used node-link representations, with "nodes" having multiple meanings, including that of river trajectories (Cai et al., 2003), or nodes also referring to "users", including the water use by cropped areas (McKinney and Savitsky, 2001). In the latter approach arcs just transfer water and only nodes change water quantity. In our approach water quantity can change in both the nodes and the arcs, and the connecting function of nodes is clearly distinguished from the water use and supply by areas, i.e. hydrotopes, in the vicinity of the nodes.

In the WW-Nile application, daily water fluxes and seasonal crop productivity are calculated by the external water and food modules at a 1km^2 pixel scale and then aggregated to the hydrotope units. The pixel level is included for modelling minor climatic variations. In the Nile basin, 1371 hydrotopes were distinguished, clustered in 120 sub-catchments (Figure S2). The water balance and productivity terms at the level of hydrotopes are input into the optimization component of WW-Nile and used as coefficients of the decision variables. The schematization further includes an aggregation to the level of the 10 riparian countries. The sub-catchments were delineated with AVSWAT (Luzio et al., 2004) based on the Digital Elevation Model of the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). AVSWAT also generated the main surface water system.

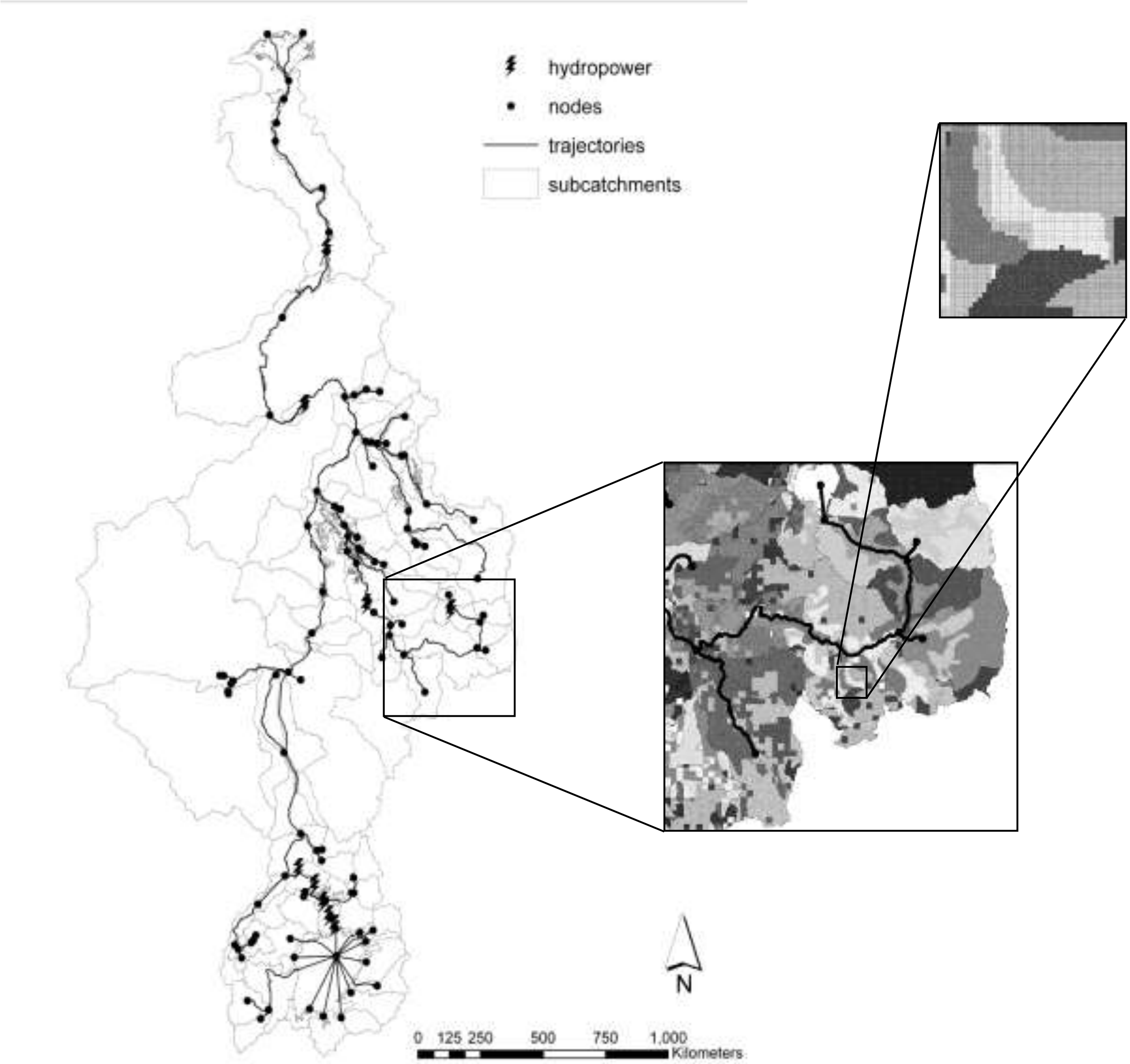

Figure S2 Surface water system with nodes and trajectories (i.e. arcs) and subcatchments of the Nile Basin with, in detail, the hydrotopes (shades of grey) and pixels (grid cells)

The model is bounded by investment costs for all major land conversions and new irrigation and hydropower schemes. Depending on the scenario, the model either optimizes total yield-over-cost or yield-over-cost for a certain sector in a specific set of countries (e.g., irrigated agriculture in Sudan and Ethiopia). The allocation of investment capital is not labeled for use in any specific country or sector. The investment strategy thus represents a situation in which a social planner (e.g., a donor agency, investor, or creditor) looks for the highest return on investment (ROI) within the whole Basin.

In the next sections, first the individual module concepts and their schematization and parameterization for the Nile application will be described. A validation of module results is given with available data on runoff for the various regions and agricultural yield estimates for the basin as a whole. Results in the form of water productivity of different uses are then presented, highlighting the difference between the value of water of the different irrigation systems and various hydropower projects. Finally, results from a limited sensitivity analysis are discussed.

2. Modules

2.1. Water module

The water balance computations are performed by a pre-processor at the basic pixel level, at a daily time step. In the Nile application a soil moisture accounting model of the bucket type is used, very similar to the Aquacrop method of the FAO (Raes et al., 2011), but more advanced in simulating soil storage and drainage while simplifying the dynamic crop growth. Rainfall in each pixel can contribute to runoff, drainage, or groundwater storage, after correcting for evapotranspiration (figure S3). The calculation scheme for the evapotranspiration follows the FAO single crop coefficient method (Allen et al., 1998), applied separately to the vegetated and non-vegetated part. The development stage of a crop is assumed to follow a pre-fixed pattern during the season, which is translated to a time-dependent crop coefficient:

$$\mathrm{ET}_p = K_c\,\mathrm{ET}_\mathrm{o} \qquad [2]$$

where ET_p is the potential evapotranspiration, ET_o is the reference crop evapotranspiration, and K_c the time-dependent crop factor. Outside the actual growing season the crop factor is also given a value, to account for the evaporation of developing shrub vegetation and bare soil. In most countries in the Nile basin the cropping system consist of a double crop rotation, with planting dates depending on the rainy seasons. Ethiopia e.g. has the short and long rains, Some parts of the Lake Victoria region have favorable crop conditions year round. In WW-Nile these double crop rotations can simply be inserted by letting the monthly K_c factor for the first crop be followed the K_c factors for the second crop in the rotation. The potential transpiration is reduced to the actual value by taking water stresses into account, like is done in the FAO AquaCrop model:

$$\mathrm{ET}_a = K_s\,\mathrm{ET}_p \qquad [3]$$

where ET_a is the actual evapotranspiration and K_s is the time-dependent soil water stress coefficient. The stress coefficient is set proportional to the water content:

$$K_\mathrm{s} = S_\mathrm{r}/S_\mathrm{opt} \quad \text{, for } S_\mathrm{r} < S_\mathrm{opt} \qquad [4]$$

$$K_\mathrm{s} = 1.0 \quad , \quad \text{for } S_\mathrm{r} \geq S_\mathrm{opt} \qquad [5]$$

where S_r is the available water root zone content above wilting point, and S_opt the lower limit of soil water content for which the transpiration retains the potential value.

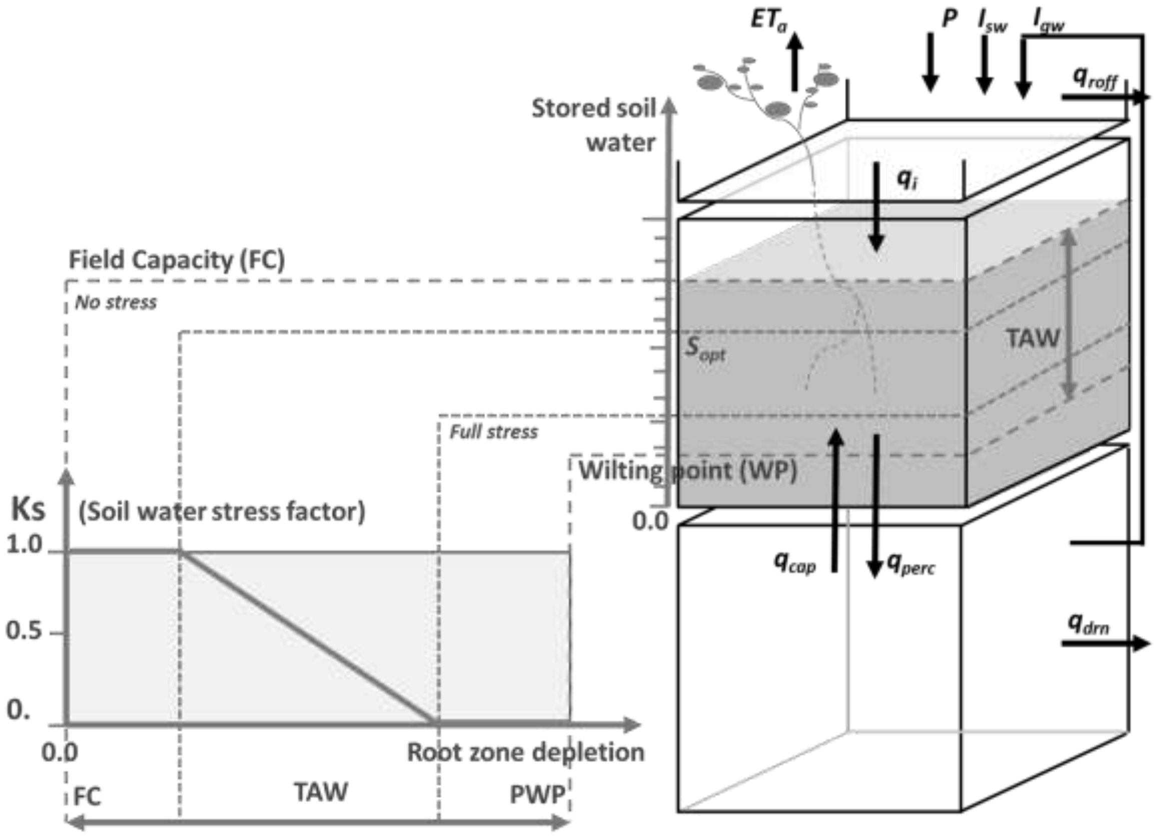

Figure S3 Water module storage components and flow terms (adapted from Raes et al., 2011)

The water storage accounting method uses three storages: one for the soil surface, one for the root zone and one for the subsoil. The accounting method starts with determining the infiltration at the soil surface. After the initial update of the soil surface storage the possible infiltration rate q_i^t is determined as the limiting value of: i). amount of water on the soil surface; ii). infiltration capacity of the soil, and; iii). available storage deficit of the soil. The soil surface is assumed to have a certain retention capacity in situations with ponding. The moisture accounting for the root zone first does the update for the flows across the upper boundary:

$$S_r^{\,t} = S_r^{\,t-1} + (P + I - ET_a)\,\Delta t \qquad [6]$$

where $S_r^{\,t}$ is the amount of water stored in the root zone, and S_{FC} is the water storage at field capacity, P is precipitation and I is irrigation. If the predicted storage is larger than the field capacity, then the excess is simulated as percolation and the storage is set equal to field capacity:

$$q_{perc}^{\,t} = (S_r^{\,t} - S_{FC})/\,\Delta t\,; \quad S_r^{\,t} = S_{FC} \qquad [7]$$

The model also has a simple provision for 'capillary rise' from the subsoil storage under extremely wet conditions; that is assumed to be the case when

$$S_g > S_{max} - S_{FC} \qquad [8]$$

where S_g is the storage in the subsoil, and S_{max} is the storage capacity of the whole profile, taken with respect to a certain datum plane. A second requirement for simulating capillary rise is that the root zone water content has dropped below S_{opt}, meaning that the actual evapotranspiration is being reduced with respect to the potential value. The drainage flux is simulated with a linear reservoir approach:

$$q_{drn} = \alpha\,(S_g - S_{g,db}) \qquad [9]$$

where α is the reservoir coefficient and the subsoil storage for the groundwater level equal to the drainage base.

In WW-Nile, a pixel can draw water from three sources: i) sustainably from its own local groundwater storage component; ii) from the local surface water storage of each sub-catchment; and iii) from the main water courses and reservoirs (Nile, Atbara etc.). Irrigation demand is triggered by the root zone moisture storage, when it has dropped below a specified fraction of S_{FC}. The demand is then computed with:

$$I_{dem} = (\mathrm{S}_{FC} - S_r)/f_{app} \qquad [10]$$

where I_{dem} is the irrigation demand and f_{app} the assumed application efficiency. The realization of the demand can be from groundwater or from surface water, or from both. In the latter case the model first tries to extract groundwater; if there is not enough available the model supplies the deficit from surface water. The amount of available groundwater is determined from:

$$q_{g,max} = (S_g - S_{g,dead})/\,\Delta t \qquad [11]$$

where $q_{g,max}$ is the maximum allowed extraction rate and $S_{g,dead}$ is the water in 'dead' storage. By not allowing extraction to draw from dead storage, the model implements the policy of sustainable mining of groundwater. Irrigation from surface water is assumed to involve extra losses. Some of these losses are recoverable, some not. Both types of losses are anticipated by increasing the demand:

$$I_{s,dem} = I_{dem}\,/(1 - f_{loss,rec} - f_{loss,nonrec}) \qquad [12]$$

where $f_{\text{loss,rec}}$ is the fraction of recoverable losses and $f_{\text{loss,nonrec}}$ of non-recoverable losses. The recoverable losses are added to the drainage term. That drainage flows back to the main waterways and becomes available for irrigation from surface water at a downstream location. Irrigation comes at a cost, made up from two components; a fixed cost in USD per ha and a variable costs in USD per m^3 of water used. Together these form the costs of local water-management measures for supporting land use (*CLWM*).

2.2. Crop module

Crop production is simulated with a slightly modified form of the K_y approach of FAO (Doorenbos and Kassam, 1979), which most holistic models use for modelling the effect of water availability on crop production. This relatively simple method has the advantage of being robust and requiring a minimum of data. For modelling a specific situation the K_y method requires less parameters than a model like AQUACROP for calibrating a good fit. In the modelling of large basins the robustness and minimum data requirement of the K_y method reduces the risk of model errors due to wrong input data. The method consists of a single modelling equation for the relative yield:

$$(1 - Y_a/Y_p) = K_y(1 - ET_a/ET_p) \qquad [13]$$

where Y_a is the actual yield, and Y_p the potential yield, with ET_a/ET_p derived from the water balance module. Values of K_y>1 are for crops sensitive to water stress as assumed here throughout. Making the equation explicit for the relative yield gives:

$$Y_a/Y_p = [ET_a/ET_p - (K_y - 1)/K_y]K_y \qquad \text{, for } ET_a/ET_p \geq (K_y - 1)/K_y \qquad [14]$$

$$Y_a/Y_p = 0 \qquad \text{, for } ET_a/ET_p < (K_y - 1)/K_y \qquad [15]$$

This relationship takes into account that the available water has to exceed a certain threshold for the production of a harvestable product[1]. What it does not take into account is that with increasing degree of water supply there will be diminishing returns for the crop production, meaning that the productivity curve has an S-form. In the WW-Nile model this has been schematically introduced by adding an extra intercept parameter for when the relative productivity reaches 1.0 (Figure S4)[2]:

[1] Formal representation of this threshold introduces a strong nonlinearity in a mathematical programming model, especially if used in combination with land use area as an endogenous decision variable. Therefore the threshold is usually disregarded in the model formulation, e.g. in the Zambezi model of Tilmant et al. (2012). The consequence can be that for K_y>1 their model is forced to supply water to meet the feasibility constraint (non-negative yield), but that the yield is exactly at zero. This we consider an avoidable loss of optimality. In the IBMR model of Yang et al. (2012) the soil-water-plant water balance is directly incorporated in the holistic model. Water shortage is modelled with slack variables that are used in a penalty term of the objective function. In order to avoid a negative yield (implicitly), the crop response must be made completely linear (K_y=1, no threshold).

[2] This type of nonlinearity is more often included than the zero-production threshold. Marginal returns tend to decrease as the water availability approaches the potential demand. This aspect can be modelled with a piecewise linear function using

$$Y_a/Y_p = 1.0 \quad , \text{for } ET_a/ET_p \geq f_y \qquad [16]$$

$$Y_a/Y_p = [ET_a/ET_p - (K_y-1)/K_y]\, c_y \quad , \text{for } ET_a/ET_p \geq (K_y-1)/K_y \text{ and } ET_a/ET_p < f_y \qquad [17]$$

$$Y_a/Y_p = 0 \quad , \text{for } ET_a/ET_p < (K_y-1)/K_y \qquad [18]$$

where f_y is the extra intercept parameter (within $[(K_y-1)/K_y),1]$) and c_y is given by:

$$c_y = 1/\,[\,f_y - (K_y-1)/K_y] \qquad [19]$$

In WW-Nile we used two values of the K_y factor. We assumed that on existing rainfed arable land there is scope for an improvement in crops or cropping practices over the period considered. To represent this improved cropping system, an intensive crop variant was introduced; this variant has higher input costs and a steeper production function (higher K_y) and thus a higher threshold value for crop survival (Figure S4). However, it also has a higher prices. As a result, the intensive variant was less profitable under conditions of water stress, but gave higher GM when crop water demand could be met.

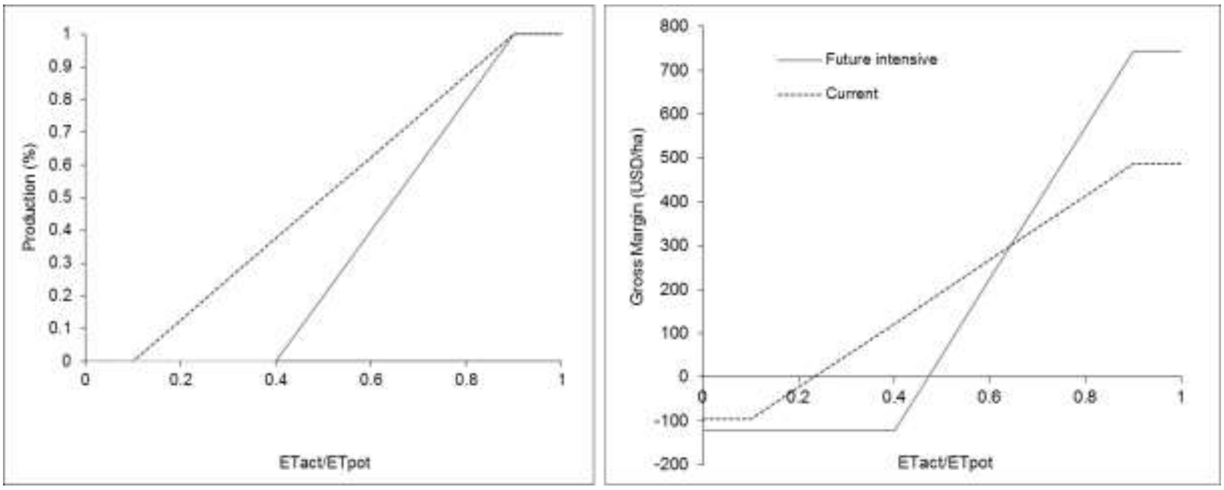

Figure S4 Crop production as a function of water availability (actual evapotranspiration/ potential evapotranspiration) and Gross Margin for a 'current' cropping system and the near-future 'intensive' option, using cost and benefits from the Maize-Potato dominated cropping system of Tanzania as an example.

only linear variables or with a quadratic function as is done in e.g. Cai (2003). We have added an extra parameter to the K_y method, for schematically modelling the reduced rate of return near the production optimum (Fig. S4)

2.3. Energy module

The WW Hydropower module has two options to calculate the yield of a hydropower scheme; one in which water level in the reservoir (head) influences the energy generated and one where the head is assumed static and flow stationary over the period considered. We choose the latter, more simplified option, as we were mainly interested in the overall yield in relation to basin-wide changes of land use and major changes to the river system, rather than focusing on optimizing the management of reservoirs in detail. In WW-Nile the storage dynamics of reservoirs are controlled by optimizing the release for hydropower and/or irrigation on a 3-monthly time step. The energy production according to the static head stationary flow method can be described as:

$$E_{hydropower,\Delta t} = \rho\, g\, h_d\, \beta\, \frac{\gamma\, V_{in,\Delta t}}{\Delta t}\, \frac{\Delta t}{3600}\, 10^{-3} \qquad [19]$$

where $E_{hydropower,\Delta t}$ is total energy produced (kWh), Δt is length of season (s), ρ is the water density (kg/m^3), g is the gravity constant (m/s^2), h_d *is* static water height at turbine (m) β is the fraction diverted for hydropower (-), γ is the turbine efficiency (-) and $V_{in,\Delta t}$ is the volume of water entering the reservoir (m^3). With ρ, g, h_d, and β constant and $\gamma\, V_{in,\Delta t}$ equal to $V_{out,\Delta t}$, this can rewritten as:

$$E_{hydropower,\Delta t} = \frac{E_{maximum\ capacity}}{V_{max}}\, \frac{V_{out,\Delta t}}{\Delta t}\, \frac{\Delta t}{3600}\, 10^{-3} \qquad [20]$$

where $E_{maximum\ capacity}$ is a function of energy produced at maximum flow (V_{max}) through the turbines. These are a site-specific characteristics depending amongst others on the height difference and the turbine size and efficiency and are generally reported for hydropower schemes. Based on this maximum capacity, maximum flow through the turbines, and a generally accepted average world market price for hydropower-generated electricity of 0.08 USD/kWh (Whittington et al., 2005), a revenue per m^3 of flow through the turbines was determined for each of the hydropower stations. Actual revenue was then calculated by the model as actual simulated flow times this revenue per m^3. No costs were included. Aggregating all hydropower revenues leads to the total GM of hydropower (Y_{HP}, in USD/yr)

Table S1 shows the existing large reservoirs and hydropower generation facilities, as well as all major proposed new dams. Figure S2 shows the location of the major hydropower dams in the main rivers within the Nile Basin. Data was collected from various sources, most of them grey literature. Cost of large scale hydropower investments are described in table S1 and range from 450 million USD to 4700 million USD for individual schemes. It is likely that these figures do not include all costs involved, like a possible reallocation of the local population.

Table S1. Characteristics of existing and potential hydropower stations in the Nile Basin (Deekker, 1972; Murakami, 1995; Shahin, 1985; Sutcliffe and Parks, 1999; www.small-hydro.com, 2012)

Country	*Hydropower station*	*Investment (million USD)*	*Capacity (MW)*	*Maximum discharge (m3/s)*
Uganda	Owen Falls	Existing	300	1800
Ethiopia	Tis Abbay I&II, Tana - Beles	Existing	544	180
Sudan	Roseires	Existing	210	1689
Egypt	Aswan Old Dam and High Dam	Existing	2600	4152
Uganda	Bujugali	730	250	1316
Uganda	Kalagala	680	315	1344
Uganda	Karuma Falls	450	200	577
Uganda	Ayago, Murchison	1000	800	400
Ethiopia	Grand Ethiopian Renaissance Dam	4700	5250	1750
Sudan	Merowe	1700	1250	3600

3. Validation of module output

The hydrological modeling was validated with averaged yearly water balance data for the main subcatchments (MWRI, 2005; Sutcliffe and Parks, 1999). WW-Nile runoff from the main contributing catchments corresponds well to the figures of these two studies. The impact of marshes on water losses in the White Nile, the Bahr El Gazal, and Sobat catchments was well represented. Releases at Lake Nasser were determined by irrigation demands in downstream Egypt. Water losses in Lake Nasser were calculated at 15 km^3/yr; this is higher than the often reported long-term average losses of approximately 10 km^3/yr, but corresponds to the estimated maximum evaporation loss. Overall water losses in the main surface water system (seepage and evapotranspiration, including marshes in the Bahr El Ghazal) accounted for 84 km^3/yr in the whole Basin. Total average annual water abstraction for irrigation was estimated to be 86 km^3, with 2 km^3 in the Atbara basin, 14 km^3 in the Blue Nile sub-Basin in Sudan downstream of the Roseires Reservoir and 70 km^3 in the valley and delta of Egypt. With 16 km^3, including return flows, Sudan currently abstracts several km^3 less than the 18.5 km^3 it has been allocated under the 1959 treaty. The water abstractions of 70 km^3 to Egypt support unofficial estimates, suggesting that actual releases at Aswan are higher for the period evaluated than the, often reported, officially allocated 55.5 km^3 (Nicol and Cascão, 2011). These figures include canal losses and return flows (and therefore differ slightly from values in Figure S6, which are net values).

The food module was validated with the single available FAO estimate for the Basin (Appelgren et al., 2000). The annual agricultural GM calculated for the baseline situation was 15.3 billion USD per year, which is about 35% lower than the FAO estimate. The inclusion of livestock in the latter figure, estimated at 18-35% of African agricultural GDP (Ehui et al., 2002; Sansoucy, 1995), can explain a large part of the difference. Livestock was not included in our analysis, as we focused on arable farming, which has a far larger claim on land and water resources. We assumed livestock raising to be integrated with arable farming in mixed agricultural systems, without explicit additional land and water demands. An exception to this in the Nile Basin could be the large grazing areas in Sudan and South Sudan. Conversion of these existing pastoral lands to arable lands was not restricted in the model. However, in general, the model did not select these areas for arable expansion. The mere existence of pastoral lands can, in itself, be an indication that biophysical circumstances make such lands less suitable for arable farming, for example because of erratic or strong seasonality in rainfall.

Figures on actual hydropower production for the various hydropower schemes or the region as a whole are not easily obtained. Our estimates of total energy production were thus not validated. However, the used yield value of 0.08 USD per kWh is widely accepted to as a global estimate of hydropower yields and our results will therefore mainly differ from previous model estimates (Block and Strzepek, 2010; Whittington et al., 2005), because of a different optimization of water flows.

4. Optimization mechanism: the value of water in the Nile basin

In Figure S5, water productivity of irrigation and hydropower in different countries, as derived from WW-Nile, is compared. The range of values in WW-Nile for existing irrigation schemes in Egypt and Sudan is consistent with the low (0.02 USD/m^3) and high estimates (0.08 USD/m^3) that are generally used (Whittington et al., 2005) or reported (Hellegers and Perry, 2006). New irrigation schemes in Ethiopia have a much higher productivity per m^3 applied (0.18 USD/m^3). This is a result of the relatively high effective rainfall in combination with a lower potential evapotranspiration and thus a smaller threshold deficit to be covered by irrigation for getting the revenue from the steep part of the production curve. The low productivity of Sudan's existing schemes (0.025 USD/m^3) can be explained by lower agricultural productivity due to waterlogging and siltation of canals; its maximum attainable yield is assumed to be only half of Egypt's maximum. When the existing schemes are rehabilitated, irrigation water demand in this part of Sudan becomes similar to that of Egypt, resulting in similar water productivity (0.08 USD/m^3). New irrigation schemes in Sudan are envisaged near the new Merowe reservoir in the north of the country. High evapotranspirative demand and very low rainfall result in a very high irrigation demand per hectare and a comparatively low water productivity (0.05 USD/m^3) in these schemes.

Hydropower stations with the highest water productivity (Figure S5) are mainly situated upstream in Ethiopia and Uganda, where hills and mountains provide possibilities for high dams (Ethiopian Renaissance Dam) or create natural elevation differences (Tana and Ayago-Murchison). The resulting large drop in water level delivers more MW at a lower discharge. There is no competition between hydropower and irrigated agriculture as the latter is situated mainly downstream of these high water-productive hydropower plants. In cases where there is competition, the water productivity of agriculture is higher than that of hydropower, even when adding up hydropower yields of stations in series (like Merowe and Aswan on the main Nile). As a result, irrigated agriculture will receive priority in the allocation of water. On the other hand, the existence of hydropower strengthens the prioritization of downstream irrigation. This is in line with hydro-economic principles described in previous studies focusing specifically on the interaction between hydropower and irrigation in the Basin (Block et al., 2007; Whittington et al., 2005).

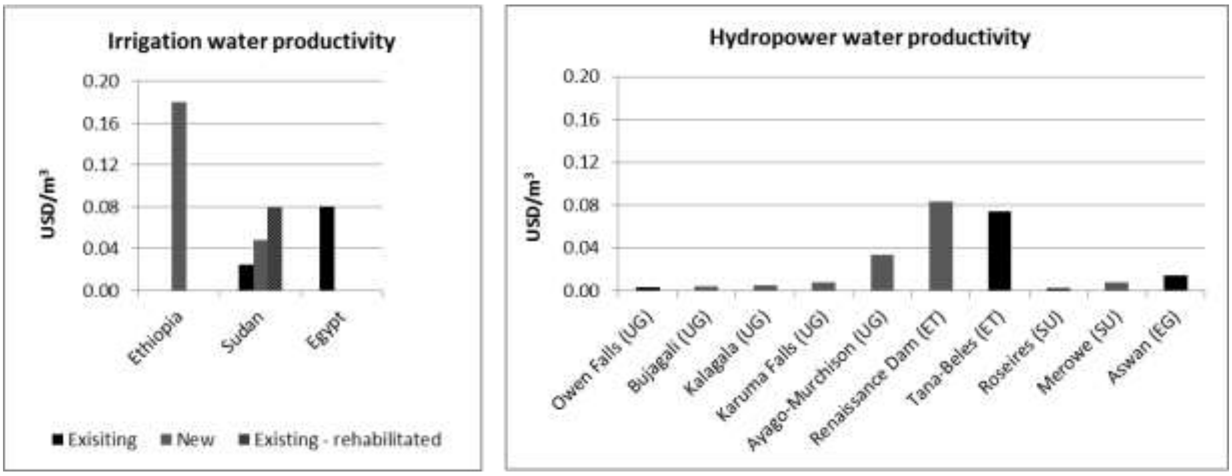

Figure S5. Water productivity for existing, new, and rehabilitated irrigation schemes. (Country averages are based on irrigation water demand, which is a result of: potential evapotranspiration minus effective precipitation times irrigation efficiency; a maximum gross margin of approximately 1800 USD/ha for new/rehabilitated schemes (and 600 USD/ha for degraded schemes in Sudan); and for existing and (potential) new hydropower stations (based on a kWh price of 0.08 USD, with UG = Uganda, ET = Ethiopia, SU = Sudan and EG = Egypt).

5. Sensitivity analysis of economic parameters

A partial sensitivity analysis was performed on three parameters: the yield of hydropower, the yields of the current irrigation scheme in Sudan (which are lower than Egypt's and difficult to estimate with precision), and the investment cost of land cover change. Together, these three parameters determine the balance in prioritizing hydropower, irrigation agriculture, or rainfed agriculture. Values were increased and decreased by 25% in the 'basin cooperation' scenario. Varying the price of hydropower (0.08 USD/kWh +/- 0.02 USD/kWh) has a direct impact on the revenues from hydropower itself, but does not tip the balance between the ROI of hydropower and land use investments. Varying the yields of Sudan's current irrigation also does not change the outcome much in terms of total Basin food production. Under both an increase and decrease, Sudan actually increases its food production slightly. With 25% lower yields under the current irrigation schemes, there is more incentive to invest in their rehabilitation at the cost of some conversion to rainfed agriculture in Ethiopia, as this leads to a higher ROI, buffering overall Basin loss in GM. With 25% higher yields, the part not rehabilitated keeps providing slightly higher GM for Sudan, leading to overall higher total Basin GM as well. Varying the investment costs of land use conversion has an effect on food production and total basin GMs, but does not alter the main outcomes. With 25% lower investment costs, more land can be converted, leading to a 2 billion USD increase in agricultural and total GM. With 25% higher costs, agricultural GM decreases by only 1.3 billion USD; that is because Sudan partly compensates for the higher costs of land use conversion by rehabilitating more irrigated area and converting less rainfed area.

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