Application of the Water Evaluation And Planning (WEAP) Model to Simulate Current and Future Water Demand in the Blue Nile

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Abstract

The riparian countries of the Nile have agreed to collaborate in the development of its water resources for sustainable socioeconomic growth. Currently there is significant potential for expansion of hydropower and irrigation in the Blue Nile River in both Ethiopia and Sudan. However, the likely consequences of upstream development on downstream flows have not been fully assessed and the water resource implications of development in both countries are unclear. Against this background, the Water Evaluation And Planning (WEAP) model was used to provide an assessment of both the current situation and a future (2015) scenario. The future scenario incorporated new irrigation and hydropower schemes on the main stem of the Nile and its principal tributaries. Data for all existing and planned schemes were obtained from the basin master plans as well as from scheme feasibility studies. Water use was simulated over a 32-year period of varying rainfall and flow. Preliminary results indicate that currently irrigation demand in Sudan is approximately 8.5 Bm^3y^{-1} for 1.16 million hectares (mha). This compares to a total irrigation demand in Ethiopia of just 0.2 Bm^3y^{-1}. By 2015, with many existing schemes being extended in Sudan and new schemes being developed in both countries, irrigation demand is estimated to increase to 13.4 Bm^3y^{-1} for 2.13 mha in Sudan and 1.1 Bm^3y^{-1} for 210 thousand hectares (tha) in Ethiopia. The flow of the Blue Nile is estimated to decline from an average of 46.9 Bm^3y^{-1} to 44.8 Bm^3y^{-1} at the Ethiopia-Sudan border and from a current average of 43.2 Bm^3y^{-1} to 36.2 Bm^3y^{-1} at Khartoum (including evaporation from all reservoirs). Although total flows are reduced, greater regulation results in higher dry season flows at both locations.

Introduction

The Blue Nile River (known as the Abay in Ethiopia) is the most important tributary of the Nile River, providing over 62% of the Nile's flow at Aswan (World Bank, 2006). Both Egypt, and to a lesser extent Sudan, are almost wholly dependent on water that originates from the Nile. This dependency makes the challenges of water resources management in this region an international issue (Waterbury, 2002).

The Blue Nile rises in the Ethiopian highlands in the region of West Gojam and flows northward into Lake Tana, which is located at an elevation of just under 1,800 m (Figure 1). It leaves the southeastern corner of the Lake, flowing first south-east, before looping back on itself, flowing west and then turning north-west close to the border with Sudan. In the highlands, the basin is composed mainly of volcanic and Pre-Cambrian basement rocks with small areas of sedimentary rocks. The catchment is cut by deep ravines in which the major tributaries flow. The valley of the Blue Nile itself is 1,300 m deep in places. The primary tributaries in Ethiopia are the Beshio, Jema, Muger, Guder, Finchaa, Anger, Didessa and Dabus on the left bank and the Chemoga, Timochia, Bir and Beles on the right bank. The Blue Nile enters Sudan at an altitude of 490 m.a.m.s.l and just before crossing the frontier, the river enters a clay plain, through which it flows to Khartoum. The average slope of the river from the Ethiopian frontier to Khartoum is only 15 cm km^{-1}. Within Sudan, the Blue Nile receives water from two major tributaries draining from the north, the Dinder and the Rahad, both of which also originate in Ethiopia. At Khartoum the Blue Nile joins the White Nile to form the main stem of the Nile River.

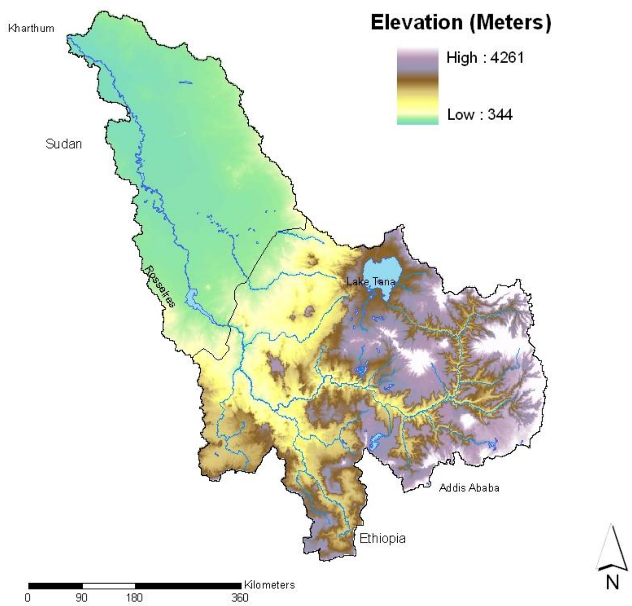


Figure 1: Map of the Blue Nile basim showing elevation, the main tributaries and key geographic features (Source: Awulachew, 2008)

Within the basin rainfall varies significantly with altitude and is considerably greater in the Ethiopian highlands than on the Plains of Sudan. Within Sudan, the average annual rainfall over much of the basin is less than 500 mm. In Ethiopia, it increases from about 1,000 mm near the Sudan border to between 1,400 and 1,800 mm over parts of the upper basin and exceeds 2,000 mm in some places. The flow of the Blue Nile is characterized by extreme seasonal and inter-annual variability. At the Sudan–Ethiopia border total annual flow varies from approximately 31 Bm^3 to 70 Bm^3. Typically, more than 80% of the flow occurs during the flood season (July to October) while only 4% of the flow occurs during the dry season (February to May).

Currently Ethiopia utilizes very little of the Blue Nile water, partly because of its inaccessibility and partly because the major centers of population lie outside of the basin. To date only two relatively minor hydraulic structures have been constructed in the Ethiopian part of the catchment (Table 1). These two dams (i.e., Chara Chara weir and Finchaa) were built primarily to provide hydropower. The combined capacity of the power stations they serve (218 MW) represents approximately 30% of the total currently installed power capacity of the country (i.e., 731 MW of which 90% is hydropower) (World Bank, 2006). The Chara Chara weir regulates outflow from Lake Tana for the downstream Tis Abay power stations. Agriculture, which is the main occupation of the inhabitants in the basin is primarily rainfed with almost no irrigation. Although there is some informal small-scale irrigation, currently the only formal irrigation scheme in the Ethiopian part of the catchment is the Finchaa sugar cane plantation (8,145 ha), which utilizes water after it has passed through a hydropower plant (Table 1).

In contrast to Ethiopia, Sudan utilizes significant volumes of Blue Nile water both for irrigation and for hydropower production. Two dams (i.e., Sennar and Roseires) have been constructed on the main river approximately 350 km and 620 km south-east of Khartoum (Table 1). These provide hydropower (primarily for Khartoum) as well as water for several large irrigation schemes, including the Gezira scheme (882,000 ha), which is one of the largest in the World. As well as irrigating land immediately adjacent to the Blue Nile River, some water is diverted from the Blue Nile downstream of the Roseires reservoir to the Rahad River, where it is used to supplement the irrigation of the Rahad irrigation scheme (168,037 ha). The total irrigated area in the Sudanese part of the Blue Nile is estimated to be 1,305,000 ha, for a variety of crops including cotton, sugar cane and vegetables. The installed power capacity at the two dams is 295 MW which represents 25% of the country's total generating capacity (i.e., 1,200 MW from both thermal and hydro power stations).

Table 1 Existing dams in the Blue Nile catchment

Dam	**River**	**Storage (Mm^3)**	**Built**	**Purpose**
Chara Chara	Abay	9,100$^+$	2000	Regulation of lake Tana outflows for hydropower production at Tis Abay I and Tis Abay II power stations (installed capacity – 84MW)
Finchaa*	Finchaa	2,395	1971	Regulation for hydropower production (installed capacity 134 MW) and also sugar cane irrigation (8,145 ha)
Roseires	Blue Nile	3,024	1964	Regulation for hydropower production (installed capacity 280 MW) and supply to irrigation schemes (1,305,000 ha)
Sennar	Blue Nile	930	1925	Regulation to for hydropower production (installed capacity 15 MW) and supply to irrigation scheme (1,093,502 ha)

+ this is the active storage of Lake Tana that is controlled by the operation of the weir (i.e. lake levels between 1784 masl and 1787 masl). It represents 2.4 times the average annual outflow of the lake.
* a small dam located on the Amerty river (storage 40 Mm^3) diverts water from the Amerty into the Finchaa reservoir

Both Ethiopia and Sudan, plan to increase development of the Blue Nile water resources significantly in the near future. This paper describes the use of the Water Evaluation And Planning (WEAP) model to investigate scenarios of water demand in the basin and to evaluate the likely implications of upstream development on downstream water availability. Water use was simulated over a 32-year period of varying rainfall and flow. The results reported here are preliminary results derived from initial model runs.

Method

Developed by the Stockholm Environment Institute (SEI), the WEAP model is intended to be used to evaluate planning and management issues associated with water resource development. The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. The elements that comprise the water demand-supply system and their spatial relationship are characterized within the model. The system is represented in terms of its various water sources (e.g., surface water, groundwater and water reuse elements); withdrawal, transmission, reservoirs, and wastewater treatment facilities, and water demands (i.e. user-defined sectors, but typically comprising industry, mines, irrigation and domestic supply) (SEI, 2007; Yates *et al*., 2005).

Typically the model is first configured to simulate a “baseline” year, for which the water availability and demands can be confidently determined. It is then used to simulate alternative scenarios to assess the impact of different development and management options. The model optimizes water use in the catchment using an iterative Linear Programming algorithm, the objective of which is to maximize the water delivered to demand sites, according to a set of user-defined priorities. When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites given the lowest priority.

In this study, the model was set-up to simulate three scenarios: i) the natural situation with no abstractions, ii) the current situation and iii) future demand in approximately 2015. Time series of monthly naturalized flow data for the period 1960-1992, obtained from the Abay Basin Master Plan (BCEOM, 1998), were used as input data. Estimates of current irrigation and hydropower demand were derived from data provided by government ministries and agencies or from previous studies. This included information on water passing through the turbines of the power stations and water diverted for irrigation. It was necessary to make a lot of assumptions, particularly about return flows from irrigation schemes. In some cases demand estimates were derived based on demand at similar irrigation schemes, and simply weighted by the ratio of the scheme areas. Irrigation demand was allowed to vary slightly depending on rainfall determined for the rain gauge located closest to the scheme. Hence, in higher rainfall years, irrigation demand was reduced slightly. Net evaporation from Lake Tana and the reservoirs was estimated using data from the nearest meteorological station. Figure 2 shows the model configuration for the current situation.

For the 2015 scenario, the size of planned hydropower and irrigation development was derived from the basin master plans for Sudan and Ethiopia. This included both new schemes and proposed extension of existing schemes (Table 2). In Sudan it is planned to raise the height of the Roseires dam by 10m, to increase the area irrigated at several locations and to construct several new irrigation schemes. It is estimated that the total irrigated area will increase to approximately 2,126,000 ha. In Ethiopia it is planned to transfer water from Lake Tana to the Beles River (a tributary of the Blue Nile) for hydropower generation, to extend the Finchaa irrigation scheme and to develop several new irrigation schemes, in the vicinity of Lake Tana as well as in other sub-basins. It is estimated that the total formally irrigated area will increase to approximately 210,000 ha. In addition, it is planned to construct a very large dam (storage capacity 40.2 Bm^3) on the main stem of the Abay, at Karadobi, for hydropower (Table 2). Although the exact dates of completion of many of these schemes is unknown, these are the highest priority schemes in each country and, for the purposes of this study, it was assumed that they would all be completed by approximately 2015.

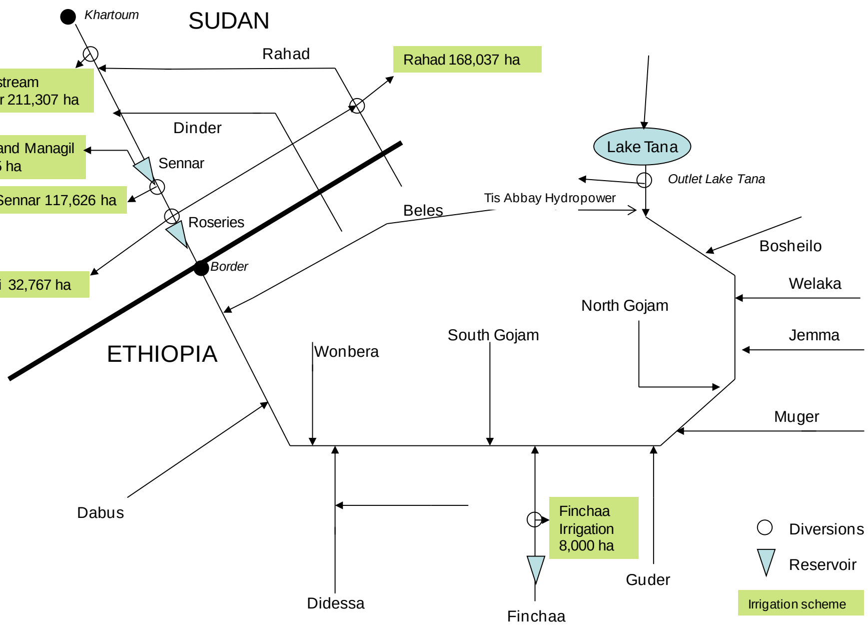


Figure 2: Schematic of the model configuration for the current situation

The water demand for new schemes was derived from basin master plans and, where available, feasibility studies. Where it is planned to extend irrigation schemes the demand was estimated based on current demand, but weighted by the new area. Again for the irrigation schemes some variability was simulated to allow for differences in rainfall. Figure 3 shows the model configuration for the 2015 scenario.

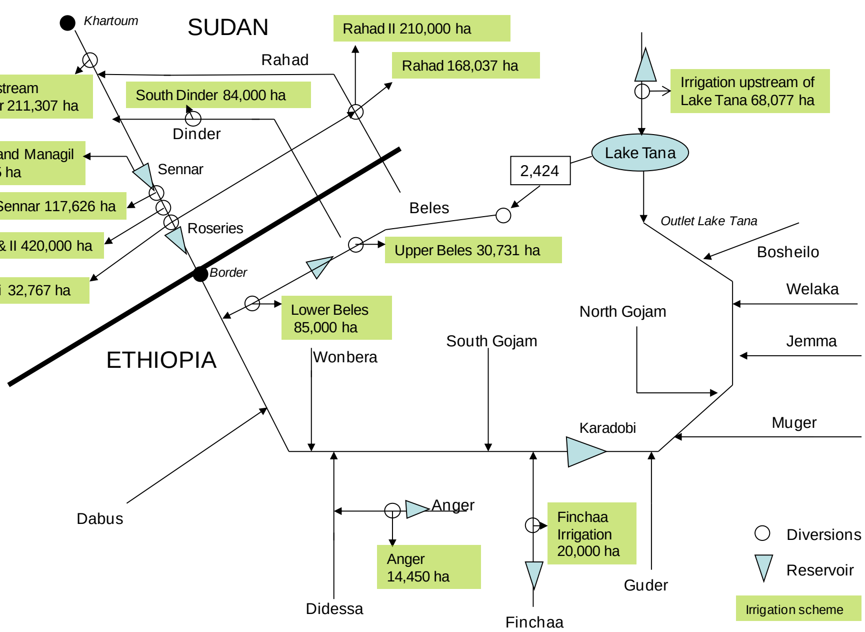


Figure 3: Schematic of the model configuration for the 2015 scenario

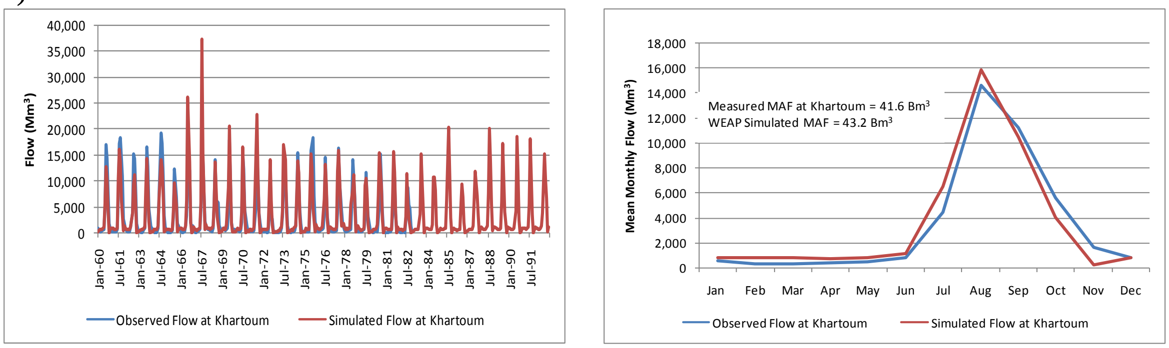
Table 2 Planned water resource development in the Blue Nile River basin, that it is assumed will be completed by 2015

Scheme	Sub-basin	Description	Completion date
Ethiopia			
Tana-Beles transfer	Tana and Beles	Transfer of water from Lake Tana to Beles catchment for hydropower production and irrigation. Average annual transfer: 2,424 Mm^3	2009/10
Irrigation in the Lake Tana sub-basin	Lake Tana	Dams to be constructed on the major inflows to Lake Tana (i.e. Megech, Ribb, Gumara and Gilgel Abay). Total storage: 1028 Mm^3 Irrigation area: 61,853 ha Average annual demand: 516 Mm^3	2012/14
Irrigation in the Beles sub-basin	Beles	Upper Beles scheme 30,731 ha Lower Beles scheme 85,000 ha Average annual demand: 1,554 Mm^3	Unknown
Extension of the Finchaa irrigation scheme	Finchaa	Extension from the west bank to the east bank using flow regulated by the existing Finchaa dam Additional irrigation area: 12,000 ha Average annual demand: 512 Mm^3	Unknown
Karadobi hydropower scheme	Blue Nile main stem	250 m high dam Total storage: 40,220 Mm^3 Live storage: 17,300 Mm^3	Unknown
Angar irrigation and hydropower scheme	Angar	Maximum irrigated area: 14,450 ha Average annual demand 202 Mm^3 Hydropower Capacity: 1.8 – 9.6 MW	2012(?)
Sudan			
Raising Roseires dam	Blue Nile main stem	Roseires dam raised by 10m to provide total (gross) storage of 7,400 Mm^3	2012(?)
Extension of Rahad irrigation scheme	Rahad	Additional irrigation area: 19,740 ha Rahad II irrigation scheme: 210,000 ha Total average annual demand: 2,432 Mm^3	2015
Extension of Suki irrigation scheme	Blue Nile main stem	Additional irrigation area: 2,940 ha Total average annual demand: 202 Mm^3	2015
Extension of Upstream Sennar	Blue Nile main stem	Additional irrigation area: 39,910 ha Total average annual demand: 749 Mm^3	2015
Extension of Downstream Sennar	Blue Nile main stem	Additional irrigation area: 44,110 ha Total average annual demand: 1420 Mm^3	2015
Kenana II and III	Blue Nile main stem	Additional irrigation area: 420,000 ha Average annual demand: 2,352 Mm^3	2015
South Dinder	Dinder	Additional irrigation area: 84,000 ha Average annual demand: 541 Mm^3	2015

Results

Figure 4 shows the simulated and observed flows at the Ethiopia-Sudan border and at Khartoum for the current situation. These results indicate that the WEAP simulation is reasonably good. At Khartoum, observed data (obtained from the Global Data Runoff Centre) were only available for the period 1960-1982. Over this period the percentage error in the simulated mean annual flow was 3.7%. As a result of current abstractions, primarily for irrigation in Sudan, the flow at Khartoum is estimated to be approximately 7.5 Bm^3y^{-1} less than would occur naturally (i.e. 41.7 Bm^3y^{-1} rather than 49.3 Bm^3y^{-1}). At the border there are two flow gauging stations. One is operated by the government of Ethiopia and just a few kilometers downstream another is operated by the government of Sudan. Possibly because of differences in periods of missing data, observed flows at these two stations differ and there is a 10% difference in mean annual flow; 50.6 Bm^3 measured by Ethiopia and 45.6 Bm^3 measured by Sudan. Without detailed analysis, which was beyond the scope of the present study, it is not possible to know which of the two flow series is the more accurate. The WEAP model simulation actually lies between the two, but is closest to the Sudanese estimate with a mean annual discharge of 45.8 Bm^3.

a)



b)

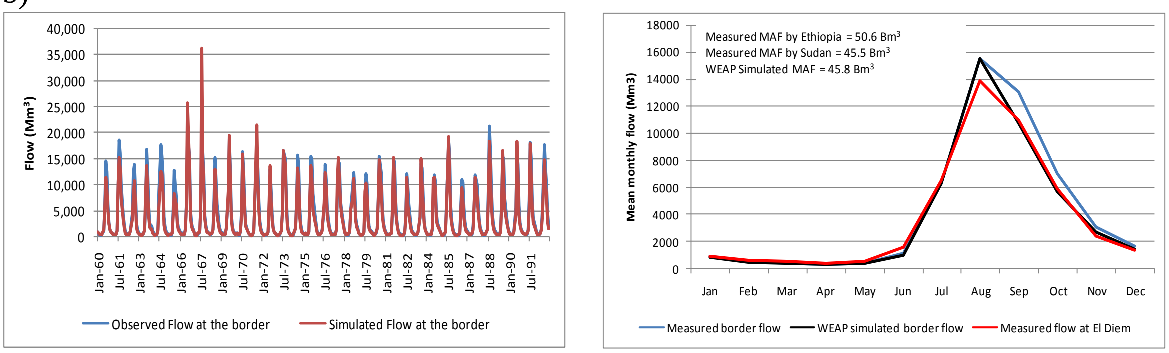


Figure 4: Simulated and observed flow series and mean monthly flows for the Blue Nile at: a) Khartoum and b) the Ethiopia-Sudan border

Figure 5 shows the simulated water levels in the Roseires and Sennar reservoirs for the current situation. Although there are no available observed data to compare with these simulated results, they do indicate how both reservoirs are operated to fill and empty each year in an attempt to reduce siltation. In some low flow years the Roseires reservoir does not fill completely.

a) b)

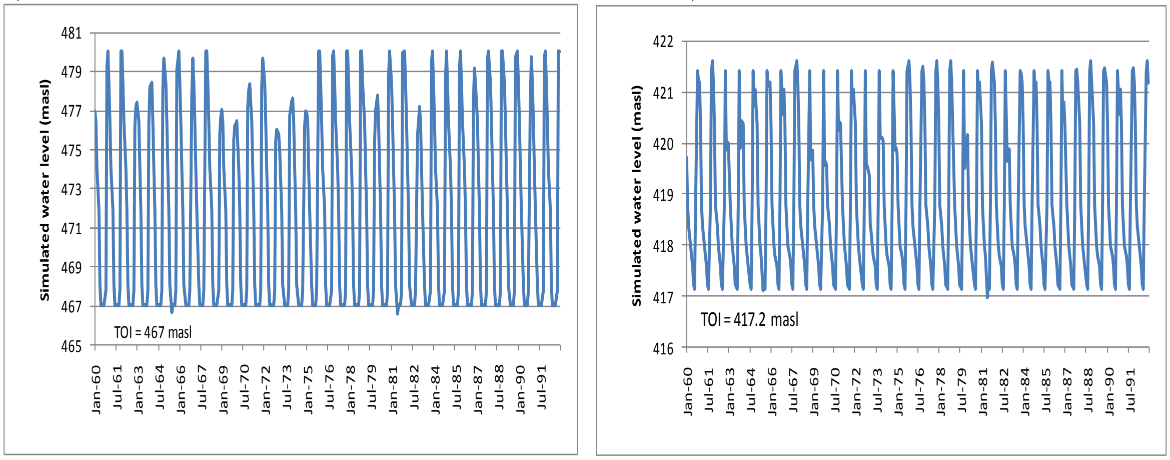


Figure 5: Simulated water levels under current conditions in a) the Roseires reservoir and b) the Sennar reservoir, Sudan

Currently irrigation water demand in Sudan greatly exceeds that in Ethiopia. Although there is some inter-annual variation, reflecting differences in rainfall, total irrigation demand in Sudan is currently estimated to average 8.5 Bm^3y^{-1} (Figure 6). This compares to an average of just 0.20 Bm^3y^{-1} in Ethiopia. With the planned irrigation development, demand in Sudan is estimated to increase to 13.4 Bm^3y^{-1} and in Ethiopia to 3.7 Bm^3y^{-1} by 2015 (Table 3). Hydropower generated in Ethiopia is currently estimated to be 1,298 $GWhy^{-1}$. With the construction of the Tana Beles transfer and the Karadobi dam this is estimated to increase to 9,930 $GWhy^{-1}$. A significant proportion of the additional electricity produced is likely to be sold to Sudan. Hydropower generated in Sudan is currently estimated to be approximately 1,000 $GWhy^{-1}$, but there are no publicly available data to confirm this estimate. Because of the additional head and increased storage, the raising of the Roseires dam will result in a very small increase in this amount.

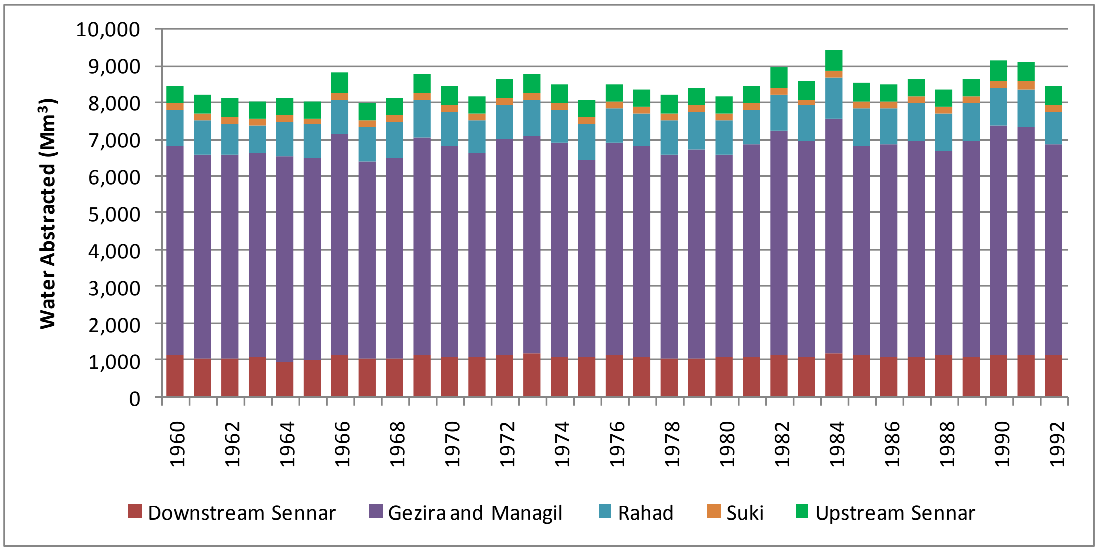


Figure 6: Estimated annual water demand for the main irrigation schemes in Sudan

Table 3 Comparison of current and future (2015) irrigation and hydropower in the Ethiopian and Sudanese parts of the Blue Nile

	Current		2015	
	Ethiopia	**Sudan**	**Ethiopia**	**Sudan**
Formal irrigation				
area (ha)	<10,000	1,305,000	210,00	2,126,000
water demand (Bm^3y^{-1})	0.20	8.49	3.69	13.43
Hydropower				
Installed capacity (MW)	218	295	2,194	295
Production ($Gwhy^{-1}$)	1,298	c.a. 1,000	9,930	ca 1,000

Comparison of the mean monthly flows at Khartoum for the simulated natural condition, current situation and the 2015 scenario indicates how the mean annual runoff is progressively reduced as a consequence of greater upstream abstractions. Wet season flows are reduced significantly but flows in the months January to May are increased as a consequence of flow regulation (Figure 7a). At the Ethiopia-Sudan border the current situation is almost identical to the natural condition so this not shown. However, in the 2015 scenario mean annual flow is reduced from 45.7 Bm^3 to 43.5 Bm^3. Similar to Khartoum there is a significant reduction in wet season flows, but increases in dry season flows as consequence of flow regulation (Figure 7b).

The 2015 scenario illustrates the benefit for Sudan of increased upstream regulation in Ethiopia. This is highlighted by the simulated water-levels in the Roseires Reservoir which show that it is possible to fill and empty the reservoir in all years (Figure 8). This contrasts with the current situation when in some years there is insufficient flow to fill the reservoir (see above) and is despite the fact that raising the dam will substantially increase the reservoir storage and irrigation demands will also have increased greatly.

a) b)

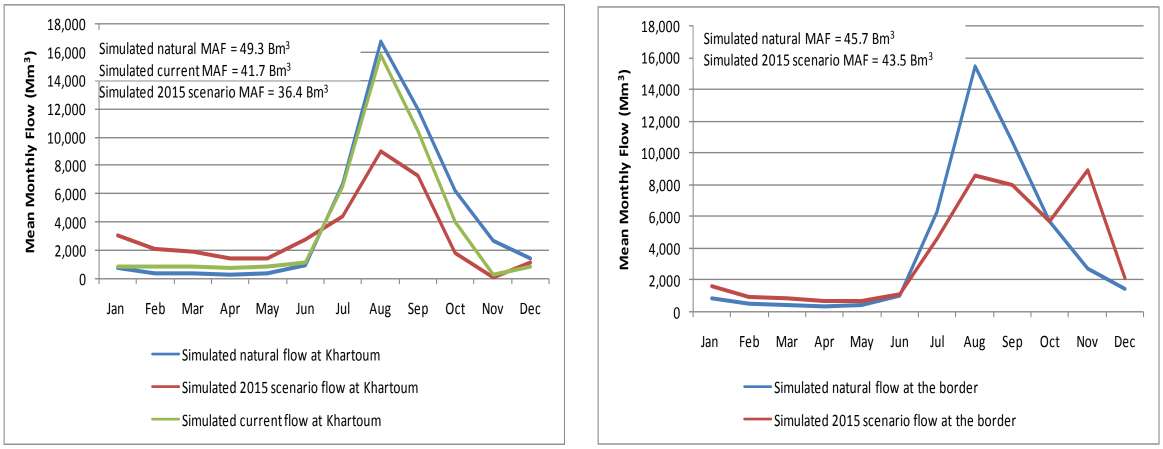


Figure 7: Comparison of simulated mean monthly flow derived for different scenarios at: a) Khartoum and b) the Ethiopia-Sudan border

a) b)

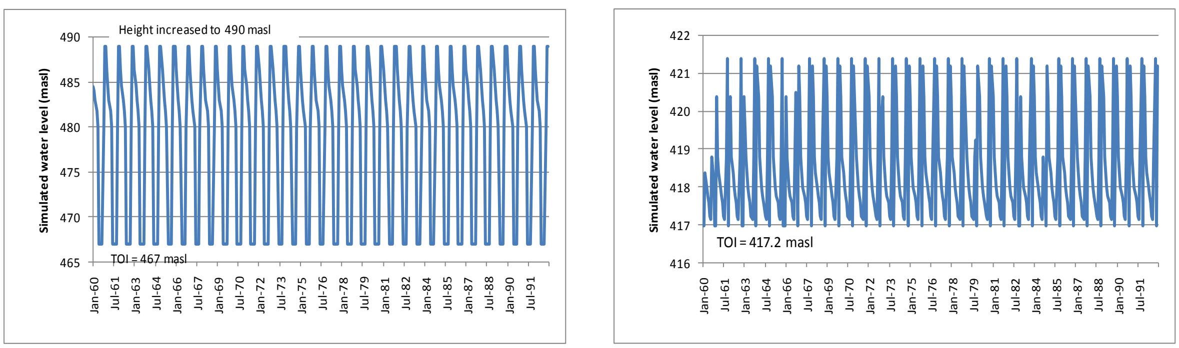


Figure 8: Simulated water levels for the 2015 scenario in a) the Roseires reservoir and b) the Sennar reservoir, Sudan

Concluding Remarks

The WEAP model has been configured to simulate the impacts of water resource development in the Blue Nile basin. Currently Ethiopia utilizes very little water but does regulate some flow for hydropower production. In contrast Sudan uses some water for hydropower production but also abstracts large volumes for irrigation. Both countries plan to develop water resource infrastructure substantially in the near future. By approximately 2015 it is estimated that the total annual consumptive demand is likely to be 17.12 Bm^3y^{-1} (i.e. 35% of the natural flow at Khartoum). Of this 3.69 Bm^3y^{-1} will be consumed in Ethiopia and 13.43 Bm^3y^{-1} in Sudan.

The results in this paper are preliminary and based on many assumptions. Where it has been possible to verify the simulations the model results are reasonable. Nevertheless, the current results must be treated with caution. In the coming months, the model will be refined using improved estimates of streamflow on the major tributaries and better estimates of irrigation demand at all schemes. In addition, it is planned to simulate another scenario based on anticipated water resource development in 2025.

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