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The impacts of Upper Blue Nile Dams construction on agricultural water availability of Sudan

Asegdew G. Mulat[a,*] and Semu A. Moges[b]

[a] Faculty of Civil and Water Resource Engineering, Blue Nile Water Institute, Bahir Dar University, Bahi Dar, Ethiopia

[b] Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA

*Corresponding author. E-mail: asegdew19@gmail.com

Abstract

The objective of this research is assessing water resource availability in the Blue Nile River for different development scenarios using Mike Hydro modeling. The long term Blue Nile total irrigation water demand will be more than $46.67 \times 10^9\ \mathrm{m}^3$, which is nearly similar to the naturalized flow (around $48 \times 10^9\ \mathrm{m}^3$). In the phase II irrigation, water shortfalls increase to $0.38 \times 10^9\ \mathrm{m}^3$/year. There is up to $2.172 \times 10^9\ \mathrm{m}^3$/year irrigation water deficit at the full development level in Ethiopia. Due to flow regulation, there are no shortfalls in irrigation in Sudan in either the medium or the long-term. Dams located in Ethiopia give more advantage to the Sudanese schemes than that of Ethiopian regarding irrigation development.

Key words: development scenarios, full development level, irrigation development, Mike Hydro, Upper Blue Nile River Basin

INTRODUCTION

Upstream Nile countries, dependent on rainfall, have experienced a greater frequency of droughts and cannot ignore the need to grow more food and expand production even at great costs; this requires irrigation (Water Watch 2009). Upstream Nile countries, pressed to find solutions to fight hunger and poverty, are trying to use their 'share' of Nile water and are planning to build multipurpose hydropower dams.

Most upstream countries are going to want more water, but water is limited and the needs are growing. This creates the potential for conflict. All Nile countries have ambitious proposals to expand irrigated agriculture to meet growing food demands and boost economic development. Based on national planning documents (Awlachew *et al.* 2012), the overall increase will be more than 10 million ha in the Nile Basin, doubling from current levels of around 5 million ha. The question is whether such plans are feasible or not. Availability of water for agriculture development in the Nile Basin lies on the balance between demand and water availability, and at what stage withdrawals by upstream countries will impact upon downstream users. The upper basin proposed irrigation development would change patterns of water availability in the Eastern Nile (Blackmore & Whittington 2008; Awlachew *et al.* 2012; McCartney *et al.* 2012).

The main challenges in the Nile basin are climate and socioeconomic changes. According to Hammond (2013), water resource management in the Nile Basin will become increasingly complex as a result of climate and socio-economic changes. The need for countries in the Nile Basin to use water resource sustainably and to expand their water infrastructure is understandable. However, basin-wide agreements present the most promising way to manage water resources. Cooperation over water is essential if countries are to develop and reduce their vulnerability to climate change. The unilateral decision making cannot provide a fruitful route to future water security. To take full advantage of the water resources of the basin, it is necessary that the basin be managed as a single system, which requires the establishment of an effective institutional mechanism that aims to develop the river in a shared-vision and cooperative way.

An investigation has to be conducted to assess the future probable changes in hydrological process that may have impacts on the availability of water. It is necessary to investigate the impacts of the newly implemented projects and expiation of irrigation on the spatial and temporal distributions of water resources in the basin.

The main objective is to simulate the Blue Nile River basin to investigate availability of water for existing and proposed development and develop an integrated basin planning framework for analyzing and prioritizing water resources development options. This involves considering different development scenarios and assessing availability of water, power production and irrigation water deficits.

DESCRIPTION OF THE REGION

The Blue Nile sub-basin

The Blue Nile sub-basin, located in the middle east of the Eastern Nile Basin (ENB), is the largest contributor to the system (56×10^9 m^3/year) accounting for 67% of the inflow at Aswan (Eastern Nile Technical Regional Office (ENTRO) 2006; Awulachew *et al.* 2008). The Blue Nile headwaters emanate at the outlet of Lake Tana in the Ethiopian highlands. The Blue Nile extends from 32° 27′ East to 39°50′ East and from 16° 5′ North to 7° 40′ North. The location map of the Blue Nile River Basin is given in Figure 1.

The Upper Blue Nile (Abbay in Ethiopia) flows out of Lake Tana at Bahir Dar City to the Ethio-Sudan Border. The Abbay, with a channel length of 922 km, falls 1,295 meters to the Sudan border (490 m.a.s.l). There is a 10-fold increase in discharge between Lake Tana and the Sudan border (ENTRO 2006). In the Ethiopian part, the Abbay is subdivided into 16 major watersheds: Dedesa, South Gojjam, Guder, Anger, Lake Tana, North Gojjam, Dabus, Beshilo, Fincha, Mugger, Jemma, Welaka, Wombera, Beles, and Rahad and Dinder at the border, constituting a total of 202,884 km^2. In the Sudan, the Abbay is known as the Blue Nile, which has three watersheds, namely the Blue Nile, the Rahad and the Dinder.

Data

The major input data prepared for the model application were stream flow data at required points, irrigation water demand for existing irrigation schemes and hydropower in the current situation. The Ethiopian Electric Power Corporation (EEPCO) Grand Ethiopian Renaissance Dam Project report, Ministry of Water Irrigation and Energy, national Meteorological agency, ENTRO, and different organizations involved in the design and consulting activities are the main sources for data collection. The data collected from different sources were compared to assure the quality of data. The generated flow data were also compared with available gauged data.

Current and future irrigation schemes in Ethiopia

Agriculture is the largest economic sector of Ethiopia, contributing about 43% of the country's GDP and employing more than 85% of the working population (CSA 2014; Teshome 2014). Production

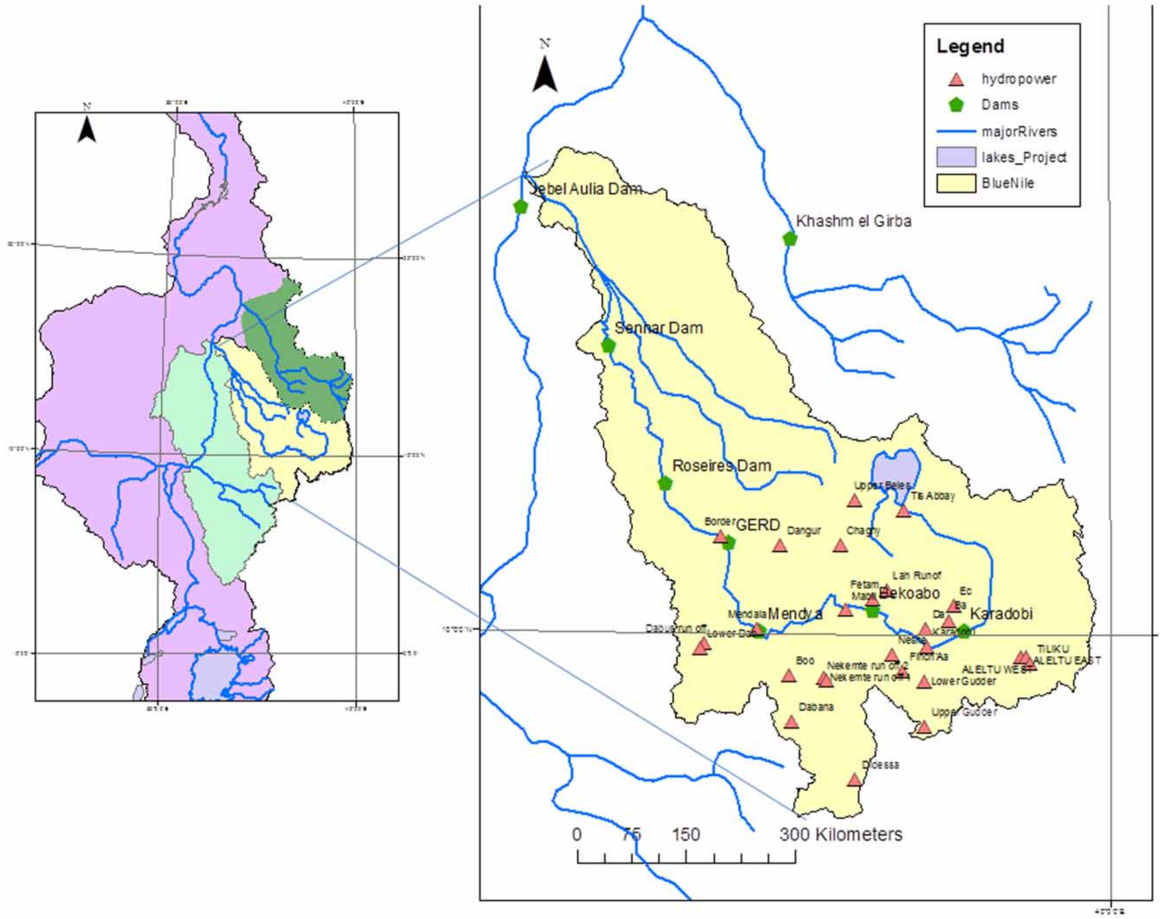

Figure 1 | Location of the Blue Nile.

systems are dominated by smallholder farming under rainfed conditions with little mechanization. Subsistence mixed farming with crop cultivation and livestock husbandry is practiced on most farms. Agriculture is highly dependent on rainfall, and hence the onset, duration, amount and distribution of the rainfall determines the performance of the agriculture sector and the economy of the country in general. More than 95% of the country's agricultural output is generated by subsistence farmers who, on average, own less than 1 ha of cultivated land with poor soil fertility as a result of continuous cropping and little input of nutrients to replace removal with harvest.

In Ethiopia, current demand is minimal compared with available resources. Ethiopia has about 3.7 million ha that can be developed for irrigation; about half of this is in the Nile Basin, but only 5–6 per cent has been developed so far (Awulachew *et al.* 2007, 2009). The current irrigated area is about 250,000 ha, with less than 20,000 ha in the Nile Basin; most of the current agricultural production is rain-fed.

The water potential of the country was not accurately known until recently. Possible Ethiopian irrigation projects have been investigated over a number of years (Lahmeyer 1962; USBR 1964; JICA 1977; WAPCOS 1990; EVDSA 1991; BCEOM 1998) and the total potential irrigated area is estimated to be 815,581 ha, comprising 45.856 ha of small-scale, 130,395 ha of medium-scale and 639,330 ha of large-scale schemes. Of this, 461,000 ha are envisaged to be developed in the long term (BCEOM 1998). In the 1960s and 1970s, comprehensive reconnaissance and feasibility studies were carried out on the Abbay (Blue Nile). Extensive studies were undertaken for the water resource potential of the Abbay River basin by Lahmeyer (1962) and USBR (1964).

In the late 1980s, an Indian firm, WAPCOS, prepared a preliminary master plan for water development for the whole country (WAPCOS 1990). On a smaller scale, pre-feasibility and reconnaissance studies of watersheds and subsidiary river valleys have been undertaken at the initiative of WRDA and EVSDA in the 1980s. There have been different estimates of the irrigation potential of the country (Table 1). According to Awlachew *et al.* (2012), one of the earliest estimations was made by the World Bank in 1973, which suggested a figure of between 1.0 and 1.5 million hectares; the Ministry of Agriculture in 1986 found the total irrigable land in the country measures 2.3 million hectares.

Table 1 | Ethiopian irrigation potential (hectares) from different sources

River	ENTRO	WAPCOS (1990)	MoWE (recent master plan)
Abbay	978,000	1,001,000	815,581
Tekeze	313,000	31,700	83,350
Baro-Akobo	749,000	98,500	1,019,523
Total	2,040,000	1,131,200	1,918,454

Most of the figures are derived by adding up the irrigation potential of the country's eight river basins. Currently, envisaged irrigation projects will cover a total of more than 174,000 ha, which represents 21% of the 815,581 ha of potential irrigation estimated in the basin (BCEOM 1998). Currently, the MoWIE (Ministry of Water Irrigation and Electricity) has identified 560 irrigation potential sites on the major river basins. The total potential irrigable land in Ethiopia is estimated to be around 3.7 million hectares.

There is very little irrigation in the Ethiopian Blue Nile catchment. Currently, the only major irrigation scheme in the Ethiopian part of the catchment is the Finchaa sugar cane plantation and Koga irrigation project. In addition to the above, however, recent development in Ethiopia through the Tana-Beles intra basin transfer enables generation of 460 MW power production and potential of development of irrigation of about 40,000 ha in the Beles Basin. Furthermore, additional small dam projects around Lake Tana are expected to improve the profile of development of irrigation access to water in the basin.

Future irrigation water demand

There is potential for additional exploitation, and both Ethiopia and Sudan plan to further develop the water resources of the river (Figure 2 and Table 2). Consequently, both countries are planning significant development of the East Nile River water resources in the future.

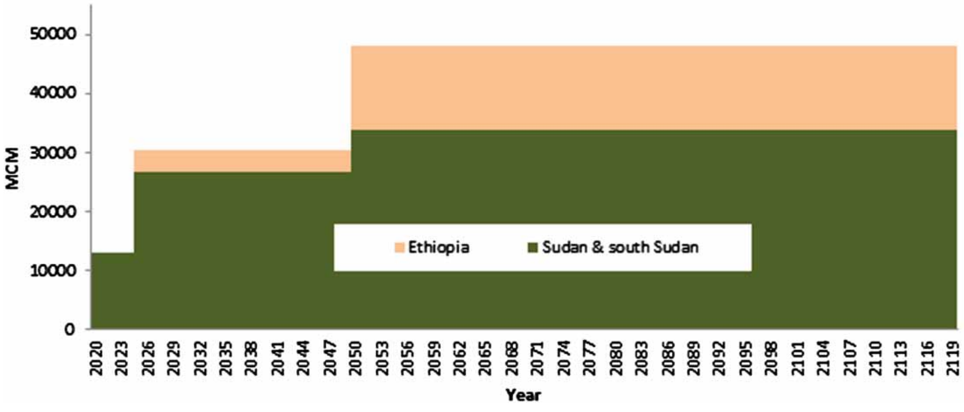

Figure 2 | Irrigation development trajectory: irrigation water demand in the Blue Nile (10^6 m^3).

Table 2 | Eastern Nile irrigation development trajectories: irrigation area (1,000 ha)

	Country	Current	Medium-term development	Long-term development
ENTRO spreadsheet	**Sudan**	1,399	1,939	2,517
	Ethiopia	140	1,028	1,392
	Total	**1,539**	**2,967**	**3,909**
Awlachew *et al.* (2012)	**Sudan**	**2,176**	**3,575**	**4,503**
	Blue Nile	1,305	2,126	2,194
	White Nile	349	587	796
	Tekeze Atbara	391	412	732
	Main Nile	131	450	781
	Ethiopia	**16**	**344**	**1,216**
	Blue Nile	16	217	490
	Baro-Akobo	0	72	537
	Tekeze Atbara	0	55	186
	Total	**2,192**	**3,919**	**5,719**

In Ethiopia, current planning is focused primarily on the Dedesa Arjo, Rahad, Dinder, location between Lake Tana and Karadobi, Lake Tana and the Beles River catchments, which have been identified by the government. Sudan is also planning to increase the area irrigated in the Blue Nile Basin (BNB). Additional new projects and extension of existing schemes is anticipated to add an additional 889,340 ha by 2025. The major planned intervention is the heightening of the Rosaries dam by about 10 m.

The water withdrawals for irrigation schemes were derived from a variety of sources, including the Ethiopia Basin master plan. For the medium-term and long-term scenarios, the sizes of planned irrigation development schemes were derived from the basin master plan for the Ethiopian Blue Nile and from the Eastern Nile Technical Regional Office (ENTRO) spreadsheet as well as from the Joint Multi-purpose Project (JMP) system inventory. For the Sudanese schemes, information on likely completion dates was obtained from the Eastern Nile Technical Regional Office (ENTRO) spreadsheet, Awlachew *et al.* (2012) and McCartney *et al.* (2012). The medium-term scenario includes the irrigation projects anticipated to be implemented before 2050.

Stochastic time series flow

Time series of monthly naturalized flow data, obtained from the MoWIE, and stochastic time series were generated for the incremental flow between water resource development structures. The monthly flows were developed through the scoping of the proposed reservoirs. These sites include: Bahir Dar to Kessie Incremental, Kessie to Karadobi Incremental, Karadobi to Mendya Incremental, Mendya to Border/Renaissance Incremental, Melaka, Kubur, Atbara wade, Rahid and Dinder. These incremental flows were available for the period from 1961 to 2002 and were developed from simple subtractions of mainstream gauges, therefore incorporating flows from tributaries already known from gauged data.

A hundred years of stream flow data were generated using Thomas-Fiering models for 42 years' observed flow data (from 1960 to 2001). Both graphical and numerical performance measures were applied in the comparison of generated and historical data. The graphical evaluation includes comparison of the simulated and observed hydrograph, and comparison of the generated and observed accumulated runoff. As shown in the graph (Figure 3), there is very good agreement between the generated and observed flow data and the rising and falling limbs have been captured. The numerical performance measures include the overall water balance error (i.e. the difference between the average simulated and observed runoff), and a measure of the overall shape of the hydrograph based on the coefficient of determination or Nash-Sutcliffe coefficient. The Nash-Sutcliffe efficiency (NSE) is normalized statistics. The comparison of the relative magnitude of the residual variance

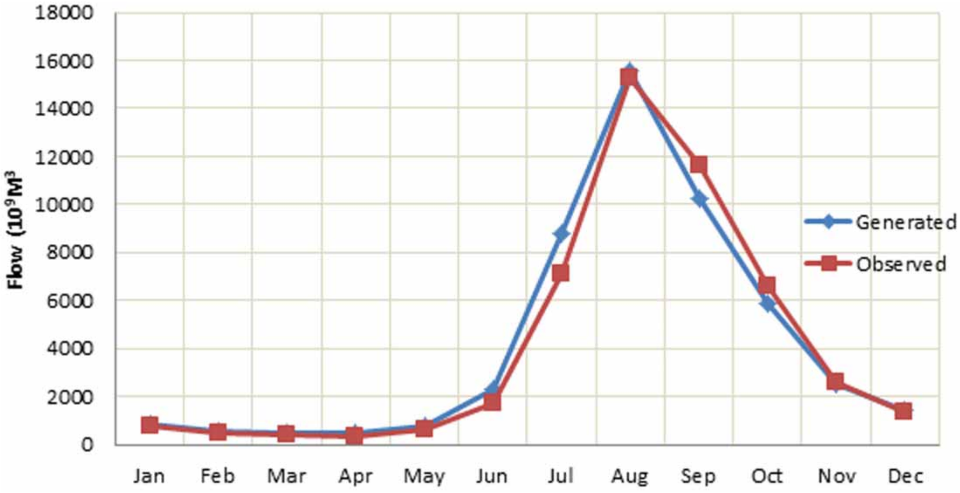

Figure 3 | Mean monthly hydrographs of observed and generated flow (10^9 m^3).

(noise) and the measured data variance (information) is determined by NSE (Nash & Sutcliffe 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi *et al.* 2007). The NSE value of 1 indicates a perfect fit.

Coefficient of determination and the Nash-Sutcliffe coefficient are 0.82 and 0.87 respectively, which indicates very good performances of the models. In the graphical comparison, all peaks and minimum flows are captured.

Hydropower and reservoirs

Hydropower data were supplied by the Ethiopian Electric Power Corporation (EEPCO) Grand Ethiopian Renaissance Dam Project study and ENTRO power toolkit. The reservoirs that are in the study level are considered as future cascade developments. The physical characteristics of the reservoirs were provided by the ENTRO power tool kit, Ministry of Water Irrigation and Electricity (MoWIE). Table 3 provides the basic physical characteristics of the reservoir sequentially from upstream to downstream.

Table 3 | Main reservoirs and proposed and implemented hydropower plants in the Blue Nile (*source*, ENTRO power tool kit)

	Hydro power (MW)				
Reservoirs/hydropower plant	**Installed capacity**	**Target power**	**Active storage**	**Country (location)**	**Remarks**
Tana Beles	460	460	9,030	Ethiopia	In operation
Karadobi	1,600	933	17,000	Ethiopia	Under study
Bekoabo high	1,940	1,329	17,400	Ethiopia	Under study
Mendia	1,700	802	1,240	Ethiopia	Under study
Bekoabo Low	935	514	10,315	Ethiopia	Under study
GERD	6,000	1,807	60,000	Ethiopia	Under construction
Rosaries	425	200	1,850	Sudan	In operation
Sennar	15	15	413	Sudan	In operation

Losses from reservoirs

Losses/gains were placed at reservoir locations within the basin to account for reservoir gains due to precipitation and losses due to evaporation. These losses represent the difference between gross precipitation on the reservoir and natural losses due to before the creation of the reservoir. All available demands are average monthly values and do not indicate any inter-annual variability. Table 4 shows the net evaporation loss from reservoirs.

Table 4 | Monthly net reservoir evaporation (mm/day) (*source*, ENTRO power tool kit and Coyne ET BELLIER and TRACTEBEL report)

Reservoir	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GERD	6.3	6.8	5.1	4.9	3.7	−0.6	−7.3	−6.6	−1.1	2.7	4.7	5.8
Rosaries	5.8	6.4	7.3	7.4	6.1	2.1	−0.9	−0.8	0.7	4.0	5.2	5.6
Sennar	6	6.2	7.6	7.4	6.3	2.1	−0.9	−0.9	0.7	4.2	5.2	5.6
Karadobi	5.7	5.8	4.5	4.4	3.3	−0.5	−6.5	−5.8	−0.9	2.6	4.2	5.4
Mendya	6.4	6.1	4.9	4.5	3.5	−0.7	−7.3	−5.0	0.6	3.9	4.9	6.0
Bekoabo	5.6	5.4	5.1	4.2	2.1	−2.2	−4.6	−1.5	0.3	2.2	3.9	4.8
Lake Tana	4.5	4.4	3.3	2.6	2.6	−1.2	−5.1	−6.1	−1.2	3.8	4.7	4.9

MODEL SETUP AND APPROACHES

Mike Hydro, formerly known as Mike Basin, is used for modeling of the Eastern Nile Basin. Mike Hydro is an integrated water resources management program that incorporates allocation, management, and planning of water resources at a river basin scale. Mike Hydro is a network model that represents rivers and tributaries by a network of branches and nodes (Yang *et al.* 2015).

The natural river system of the Eastern Nile River Basin (ENRB) was schematized and represented with a node-branch structure (Figure 4). In the simulation, only two major water demand sectors were considered: irrigation and hydropower. The major irrigation system in the basin is gravity flow (normally from reservoirs). The schemes were then allocated to the nearby nodes for their water withdrawals, and return flows from established schemes were directed to the immediate downstream nodes. Two flow series will be considered in the schematization, representing the input to the potential reservoir and the flows to the water demand area.

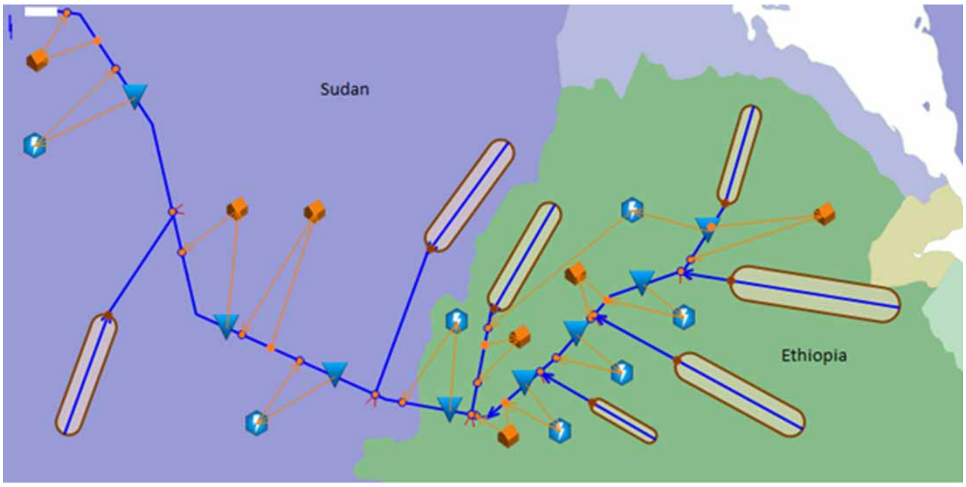

Figure 4 | Schematization of Eastern Nile for future irrigation development.

The schematization of the river basin should be such that the availability of water at major control structures and major water extraction points (users) is sufficiently represented. Individual upstream sub-basins are attached to those points. For such schematization, a differentiation should be made between a limited set of relatively important water systems with regional influence and many distributed small water users. It will usually be impossible for a larger basin to consider each individual (small) control point or user in an overall analysis of the basin, a suitable level of aggregation has to be found.

Model performance analysis

Model performance was carried out by comparing the observed flows with outputs of Mike Basin models at the selected stations of Kessie, Border and Khartoum. To facilitate the evaluation, visual as well as statistical comparison has been done. Statistical parameters such as use of Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), Mean Relative Bias (PBAIS) and Root Mean Square error (RSR) were used (Table 5).

Table 5 | Model performance: statistical values at selected site

Location	Observed Mean (MCM)	Simulated Mean (MCM)	NSE	R^2	PBAIS	RSR
Kessie	16,581	16,507	0.95	0.97	0.4	0.23
Border	48,192	48,350	0.99	0.99	−0.3	0.09
Khartoum	41,300	42,899	0.88	0.91	−0.4	0.35

The monthly stream flow has been compared against the observed data. Table 5 indicates that the total simulated monthly stream flow or NSE range $0.75 < \text{NSE} < 1.00$ for all locations, which shows very good performance rating. The coefficient of determination for all locations is 0.94, which shows very good performance of the model. (Moriasi *et al.* 2007). The percentage of bias is within the range of very good performance rating for all selected locations. The model performs very well because $0.00 < \text{RSR} < 0.50$ for the validation period of the Eastern Nile at Kessie, El-Deim, Khartoum.

Development scenarios

For many potential schemes, there is currently considerable uncertainty about the dates when they will be completed. In the current study it was assumed that, for Ethiopian schemes, if prefeasibility studies have been undertaken then the scheme will be completed in the medium term. For all other planned schemes it was assumed that they will be completed in the long term. However, clearly the two scenarios reflect only an approximate timeline for water resources development in the basin. In reality, development is dependent on many external factors and so it is impossible to predict exactly when many planned schemes will actually be implemented, or indeed the exact sequencing of schemes. As they stand, the medium-term and long-term future scenarios represent a plausible development trajectory, but it is unlikely that it will actually come to pass in exactly the way envisaged.

The model was set up to simulate four irrigation scenarios with three development stages (phases) and three dam scenarios. Table 6 represents possible future irrigation and hydropower trajectories of the Blue Nile. Table 7 shows the scenarios that result from the combination of irrigation and hydropower/dam scenarios. As shown in Table 7, there are 10 possible conditions (scenarios) for irrigation and dam combinations. The scenarios in Table 7 are the combined results of dam and irrigation development scenarios.

The current situation is the situation that represents the current level of development or the existing hydropower/dams and irrigation development. Phase I represents irrigation development projects that are under study and under construction and anticipated to be completed before 2025. Phase II is the condition when all identified Ethiopian irrigation potential has advanced either to pre-feasibility

Table 6 | Hydropower and irrigation development stages

<table>
<tr><th></th><th>2020-2025</th><th>2026-2030</th><th>2031-2035</th><th>2036-2040</th><th>After 2040</th><th>After 2050</th></tr>
<tr><td rowspan="4">Reservoirs</td><td rowspan="4">GERD filling</td><td colspan="5">GERD operation</td></tr>
<tr><td rowspan="3">Karadobi filling</td><td colspan="4">Karadobi operation</td></tr>
<tr><td rowspan="2">Bekoabo filling</td><td colspan="3">Bekoabo operation</td></tr>
<tr><td>Mendya filling</td><td colspan="2">Mendya operation</td></tr>
<tr><td rowspan="2">Irrigation</td><td rowspan="2">Current situation</td><td colspan="4" rowspan="2">Phase I (from 2025 to 2050)</td><td>Phase II (after 2050)</td></tr>
<tr><td>FDL (after 2050)</td></tr>
</table>

Table 7 | Combined scenarios of future dam/hydropower and irrigation development

	Irrigation scenarios			
Dam scenarios	Current	phase I	Phase II	FDL
current	1	4	7	
after GERD	2	5	8	
GERD and Upper cascades	3	6	9	10

or feasibility level and is anticipated to be implemented before 2050. FDL (Full Development Level) includes all irrigation potential in Ethiopia and Sudan.

RESULTS AND DISCUSSION

The results presented here are based on many assumptions on the implementation time of the development projects. There is a lack of data on flow and water demand. Thomas-Fiering models were used to generated flow data, which have reasonably accurate performance. By illustrating what may occur the scenarios provide information that is useful for resource planning, and the results provide a basis for discussion. The comparison of scenarios is the main output of this modeling task.

Flows

Increased water storage in dams and greater withdrawals will inevitably alter the flow regime of the river and its main tributaries. The planned water resources development in the basin will cause reductions in flows. The impact of water resource development on flows at key locations in the basin is summarized in Figures 5 and 6. The model results indicate that, through provision of water for hydropower and irrigation, increased water storage behind large dams is likely to contribute to economic development in the medium to long term with only marginal impacts on flow in Sudan. Comparison of the mean monthly flows in Sudan (at Khartoum) for the simulated natural condition, current situation, between 2025 and 2050 and the situation after 2050 indicates how the mean annual runoff is progressively reduced as a consequence of greater upstream abstractions.

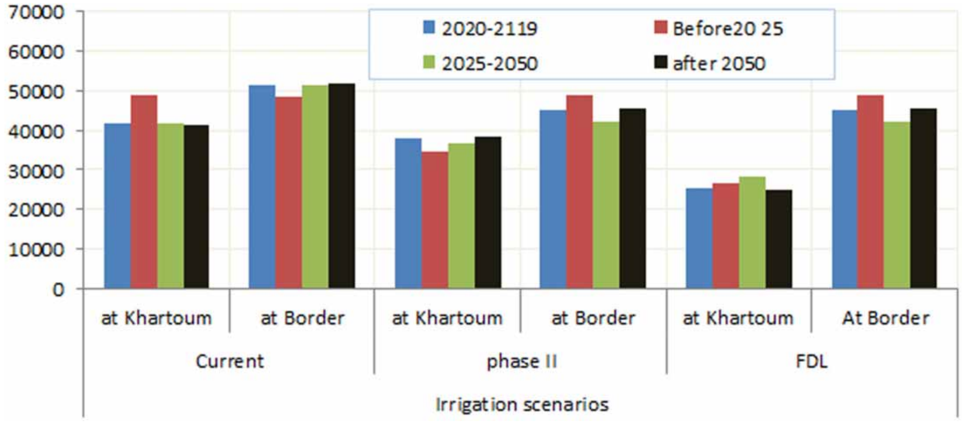

Figure 5 | Mean annual flows at selected sites (Border and Khartoum) during different stages of hydropower and irrigation development (10^9 m^3).

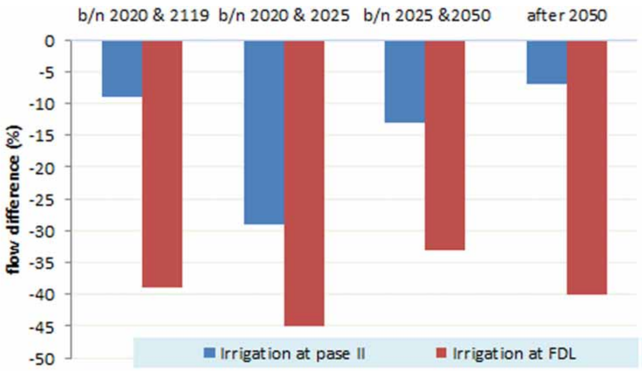

Figure 6 | Flow difference (%) at Khartoum between the current scenario and different level of future hydropower and irrigation development in the Blue Nile.

Figure 5 shows the mean annual flows at the selected locations. Figure 6 demonstrates the flow difference between the current scenario and the future development conditions. These results indicate there is decline in the flow at different locations due to the irrigation development. There are significant declines of flow at all locations at the full development level (FDL).

At the Ethiopia-Sudan border, the current situation is almost identical to the natural condition. If full development occurs, the total flow at the Ethiopia-Sudan border is predicted to decrease from the current 49×10^9 m^3 (near natural) to 42×10^9 m^3 and at Khartoum from the current 42×10^9 m^3 to 23×10^9 m^3. Sudan's future irrigation development plan in the Blue Nile is more than that of Ethiopia (Table 2), which is why there is more reduction in Khartoum than at the Ethio-Sudan border. However, although there is a significant reduction in wet season flow at both locations, the dry season flow will actually increase because of the greater upstream flow regulation. Under current conditions of the stochastic flow time series, 80–83 per cent of the river flow occurs in the wet season months (July-October). In the long-term development scenario, the wet season flow will reduce to 46–53 per cent because of the regulation effects of the upstream dams.

By increasing water availability in the dry season and reducing it in the wet season this increased regulation promises significant benefits for Sudan. The period from 2020 to 2040 is the filling time of the upper cascades. Due to that, there is maximum flow reduction at Border and Khartoum. In the full dam development scenario, flows are significantly less variable than in the other scenarios, and in the latter part of the century the periods of lowest flow are reduced slightly as a consequence of upstream storage.

The situation after 2025 (after filling of GERD) illustrates the benefit for Sudan of increased upstream regulation in Ethiopia. This is highlighted by the simulated water levels in the Rosaries

Reservoir, which show that it is possible to fill and empty the reservoir in all years. This contrasts with the current situation, when in some years there is insufficient flow to fill the reservoir and is despite the fact that raising the dam will substantially increase the reservoir storage, and irrigation demands will also have increased greatly.

Irrigation water

Currently, irrigation water withdrawals in Sudan greatly exceed those in Ethiopia because of the differences in irrigated area. The total irrigation demand in Sudan is estimated to average $13.67 \times 10^9\,m^3$/year. This compares with an average of just $0.367 \times 10^9\,m^3$/year in Ethiopia. With the planned irrigation development, demand is estimated to increase to $18.5 \times 10^9\,m^3$/year and $4.83 \times 10^9\,m^3$/year in the medium-term scenarios, and to $32.2 \times 10^9\,m^3$/year and $14.4 \times 10^9\,m^3$/year in the long-term scenarios in Sudan and Ethiopia, respectively (Table 8).

Table 8 | Irrigation water demand, used water and water demand deficits in ($10^6\,m^3$)

	Ethiopia			**Sudan**		
Scenario	**Demand**	**Used**	**Deficit**	**Demand**	**Used**	**Deficit**
1	367	367	0	13,670	13,670	0
2	367	367	0	13,670	13,670	0
3	367	367	0	13,670	13,670	0
4	4,827	4,443	384	13,670	13,670	0
5	4,827	4,443	384	13,670	13,670	0
6	4,827	4,443	384	13,670	13,670	0
7	4,827	4,443	384	18,500	18,460	40
8	4,827	4,443	384	18,500	18,500	0
9	14,447	11,775	2,172	18,500	18,500	0
10	14,447	11,775	2,172	32,190	30,935	1,255

Both Ethiopia and Sudan have plans to unilaterally develop the water resources of the Blue Nile for hydropower and irrigation. The extent to which this plan will actually be implemented is unclear. However, if both countries totally fulfill their stated objectives, the following are estimated to occur: large-scale irrigation withdrawals in Sudan will increase from the current 13.67 to $32.2 \times 10^9\,m^3$/year and large-scale irrigation withdrawals in Ethiopia will increase from the current 0.367 to $14.47 \times 10^9\,m^3$. The long term Blue Nile total irrigation water demand will be more than $46.67 \times 10^9\,m^3$, which is nearly similar to the naturalized flow (around $48 \times 10^9\,m^3$).

Table 6 shows the irrigation water demands, used water and irrigation water demand deficit of Ethiopia and Sudan. In the first column, scenarios 1 and 2 are the current irrigation water uses and current reservoir operation. In these scenarios, there is no water demand deficit in Egyptian and Sudanese irrigation schemes.

Currently, shortfalls in Ethiopia are negligible. However, in the medium-term scenario shortfalls increase to $0.38 \times 10^9\,m^3$/year (Table 6). All the medium- and long-term irrigation schemes of Ethiopia are not on the main river. They are located in the tributaries (Dedesa, Anger, Fincha, inflow to Lake Tana, Raha, Dinder Rivers). There is an irrigation water demand deficit in Ethiopia, especially in the Lake Tana demands. There is up to $2.172 \times 10^9\,m^3$/year deficit in the long term irrigation development of Ethiopia.

Because of water abstraction from the main river, which is regulated by big upstream reservoirs, there is little or no irrigation water demand deficit in Sudan due to Ethiopian irrigation development. Because of the improved flow regulation there are no shortfalls in irrigation in Sudan in either the medium (between 2025 and 2050) or the long term (after 2050). These results reflect the fact that, if irrigation development is considered, the four dams located in Ethiopia give more advantage to the Sudanese schemes than that of Ethiopian regarding irrigation development.

CONCLUSION

The aim of this study is to investigate the availability of water for the planned projects by considering different development scenarios. This involves assessing the level of irrigation water deficit and changes in hydrological process. The natural river system of the Blue Nile River Basin was schematized and represented with a node-branch structure. All the necessary features of the basin were represented by nodes connected by links. The model simulation was done for 10 scenarios from combinations of irrigation and dam that consider different development phases starting from the baseline to full development level.

If both Ethiopia and Sudan totally implement their plans, water withdrawal for irrigation will increase from 13.67 to $32.2 \times 10^9\,\text{m}^3$ /year and from 0.367 to $14.47 \times 10^9\,\text{m}^3$ in Sudan and Ethiopia respectively. The long term Blue Nile total irrigation water demand will be more than $46.67 \times 10^9\,\text{m}^3$, which is nearly similar to the naturalized flow (around $48 \times 10^9\,\text{m}^3$). If full development occurs, the total flow at the Ethiopia-Sudan border is predicted to decrease from the current $49 \times 10^9\,\text{m}^3$ to $42 \times 10^9\,\text{m}^3$ and at Khartoum from the current $42 \times 10^9\,\text{m}^3$ to $23 \times 10^9\,\text{m}^3$. In the full dam development scenario, flows are significantly less variable than in the other scenarios, and in the latter part of the century the periods of lowest flow are reduced slightly because all reservoirs are at their operation level.

Ethiopian irrigation shortfalls in the current situation are negligible. However, in the phase II shortfalls increase to $0.38 \times 10^9\,\text{m}^3$/year and at the full development level the deficit increases to $2.172 \times 10^9\,\text{m}^3$/year. Because of the improved flow regulation there are no shortfalls in irrigation in Sudan in either the medium (between 2025 and 2050) or the long term (after 2050). These results reflect the fact that, if irrigation development is considered, the four dams located in Ethiopia give more advantage to the Sudanese schemes than that of Ethiopian regarding irrigation development.

In the Ethiopian highlands, there are proposals to construct high-altitude reservoirs with the potential to reduce evaporative losses and minimize flooding in downstream areas. The total annual energy production in Ethiopia will increase to about 38,182 GWh, boosting the regional energy pool of the Eastern Nile by 258%.

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