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Simulating current and future water resources development in the Blue Nile River Basin

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Key messages

- Both Ethiopia and Sudan have plans to unilaterally develop the water resources of the Blue Nile for hydropower and irrigation. The extent to which these plans will actually be implemented is unclear. However, if both countries totally fulfil their stated objectives the following are estimated to occur:
  - the total reservoir storage in Ethiopia will increase from the current 11.6 to more than 167 billion cubic metres (i.e. more than 3 times the mean annual flow at the Ethiopia–Sudan border);
  - large-scale irrigation withdrawals in Sudan will increase from the current 8.5 to 13.8 billion m^3 yr^{-1};
  - large-scale irrigation withdrawals in Ethiopia will increase from the current 0.26 to 3.8 billion m^3 yr^{-1}; and
  - electricity generation in Ethiopia will increase from the current 1383 to 31,297 gigawatt hours (GWh) yr^{-1}.
- Increased water storage in dams and greater withdrawals will inevitably alter the flow regime of the river and its main tributaries. If full development occurs, the total flow at the Ethiopia–Sudan border is predicted to decrease from the current (near natural) 45.2 to 42.7 billion m^3 yr^{-1} and at Khartoum from the current 40.4 to 31.8 billion m^3 yr^{-1}. However, although there is a significant reduction in wet season flow at both locations, dry season flow will actually increase because of the greater upstream flow regulation. By increasing water availability in the dry season and reducing flooding in the wet season this increased regulation promises significant benefits for Sudan.
- There is great potential for increased water resources development in the Blue Nile. However, if Ethiopia and Sudan continue to implement development unilaterally, the benefits of water resources development are unlikely to be fully realized. It is therefore essential that the countries cooperate closely to (i) identify priority development options, (ii) improve irrigation efficiencies, (iii) mitigate any adverse impacts (e.g. to the environment)

and (iv) manage water resources in a way that brings benefits to all. To take full advantage of the water resources of the basin it is necessary that they are managed as a single system (i.e. without considering national borders) that, in turn, requires the establishment of much more effective institutional arrangements than those currently existing.

Introduction

The Blue Nile River is an important shared resource of Ethiopia and Sudan, and also – because it is the major contributor of water to the main Nile River – Egypt. However, tensions over the basin's water resources remain unresolved. Although the riparian countries have agreed to collaborate in principle, formal mechanisms to cooperatively develop the basin's water resources are limited. Currently, a Cooperative Framework Agreement (CFA) is being negotiated, but this process has been under way for more than a decade and no final agreement has yet been achieved (Cascão, 2009). Recently, five of the riparian countries, Ethiopia, Kenya, Rwanda, Tanzania and Uganda signed an agreement, but both Egypt and Sudan remain opposed to the current version.

Under the auspices of the Nile Basin Initiative (NBI) two primary programmes have been established: (i) the basin-wide Shared Vision Program, designed to build confidence and capacity across the basin, and (ii) the Subsidiary Action Program, which aims to initiate concrete investments and action at sub-basin level (Metawie, 2004). However, both programmes are developing slowly, and there are few tangible activities on the ground. As a result, all riparian countries continue to pursue unilateral plans for development.

The potential benefits of regional cooperation and integrated joint basin management are significant and well documented (Whittington *et al.*, 2005; Jägerskog *et al.*, 2007; Cascão, 2009). A prerequisite for such cooperation is the development of shared knowledge bases and appropriate analytical tools to support decision-making processes. Currently, knowledge of the basin is fragmented and inconsistent and there is limited sharing of data and information. There is also a lack of analytical tools to evaluate water resources and analyse the implications of different development options. These are major impediments to building consensus on appropriate development strategies and cooperative investments in the basin.

A number of computer models have been developed to assess various aspects of hydropower and irrigation potential within the Blue Nile and the wider Nile basins (Guariso and Whittington, 1987; Georgakakos, 2003; Block *et al.*, 2007; Elala, 2008). However, these models have focused primarily on the upper Blue Nile in Ethiopia and the development of hydraulic infrastructure on the main stem of the river. Relatively little attention has been paid to water diversions and development on the tributaries or future development in Sudan.

In this chapter we report the findings of research conducted to determine the impact of current and possible future water demand throughout the whole of the Blue Nile Basin (BNB). The Water Evaluation And Planning (WEAP) model was used to evaluate the water resource implications of existing and proposed irrigation and hydropower development in both Ethiopia and Sudan. The current situation and two future development scenarios were simulated; one representing a relatively near future (the *medium-term* scenario) and the other a more distant future (the *long-term* scenario). Since year-to-year variation is important for water management, 33 years of monthly time step flow data were used to simulate the natural hydrological variation in all the major tributaries. The water demands of the scenarios, incorporating all existing and planned development on both the main stem and the tributaries were superimposed on these time series. However, because the planned large reservoirs require considerable time to fill, a 20-year warm-up period was used and comparison between the scenarios was made over

13 years. Although necessarily based on many assumptions, the work illustrates how a relatively simple model, used in conjunction with data from both countries, can provide a credible basis for assessing possible future water resources development throughout the basin.

In the following section of this chapter, the natural characteristics and the current socio-economic situation in the basin as well as the planned water resources development are described. The following section describes the WEAP model and its configuration and application to the Blue Nile River Basin through development scenarios. Thereafter, the results are presented and discussed and finally some conclusions are drawn.

Water availability in the Blue Nile River Basin

Natural characteristics

The Blue Nile River (known as the Abay River in Ethiopia) 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 1800 m (Figure 14.1). It leaves the southeastern corner of the lake, flowing first southeast, before looping back on itself, flowing west and then turning northwest, 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 through which the major tributaries flow. The valley of the Blue Nile River itself is 1300 m deep in places. The primary tributaries in Ethiopia are the Bosheilo, Welaka, Jemma, Muger, Guder, Finchaa, Anger, Didessa and Dabus on the left bank, and the North Gojam, South Gojam, Wombera and Beles on the right bank.

The Blue Nile enters Sudan at an altitude of 490 masl. 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 at an elevation of 400 masl. The catchment area of the Blue Nile at Khartoum is approximately 311,548 km^2.

Within the basin, rainfall varies significantly with altitude and is, to a large extent, controlled by movement of air masses associated with the Inter-Tropical Convergence Zone. There is considerable inter-annual variability, but within Sudan the mean annual rainfall over much of the basin is less than 500 mm, and it is as low as 140 mm at Khartoum. In Ethiopia, it increases from about 1000 mm near the Sudan border to between 1400 and 1800 mm over parts of the upper basin, and exceeds 2000 mm in some places in the south (Awulachew *et al.*, 2008). The summer months account for a large proportion of mean annual rainfall: roughly 70 per cent occurs between June and September. This proportion generally increases with latitude, rising to 93 per cent at Khartoum.

Potential evapotranspiration also varies considerably, and, like rainfall, is highly correlated with altitude. Throughout the Sudanese part of the basin, values (computed using the Penman–Monteith method; Monteith, 1981) generally exceed 2200 mm yr^{-1}, and even in the rainy season (July–October) rainfall rarely exceeds 50 per cent of potential evapotranspiration. Consequently, irrigation is essential for the growth of crops. In the Ethiopian Highlands potential evapotranspiration ranges from approximately 1300 to 1700 mm yr^{-1} and, in many places, is less than rainfall in the rainy season. Consequently, rain-fed cultivation, producing a single crop in the rainy season, is possible, though risky in low rainfall years.

The flow of the Blue Nile is characterized by extreme seasonal and inter-annual variability.

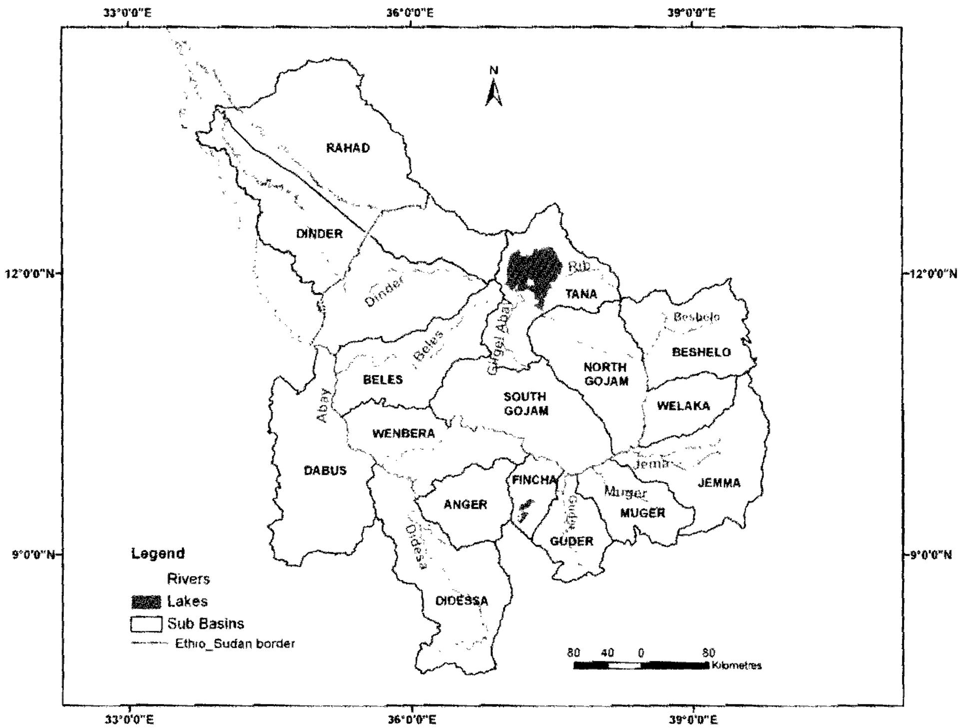


Figure 14.1 Map of the Blue Nile Basin showing the major tributaries and sub-basins

Source: Yilma and Awulachew, 2009

At Khartoum, annual flow varies from approximately 23 billion to 63 billion m^3 (Figure 14.2). Mean monthly flow also varies considerably at all locations along the river (Table 14.1; Figure 14.3). Typically, more than 80 per cent of the flow occurs during the flood season (July–October) while only 4 per cent of the flow occurs during the dry season (February–May) (Awulachew *et al.*, 2008).

Current water resources development

Currently, Ethiopia utilizes very little of the Blue Nile water, partly because of its inaccessibility, partly because the major centres of population lie outside of the basin and partly because, to date, there has been only limited development of hydraulic infrastructure on the river. To date, only two relatively minor hydraulic structures (i.e. Chara Chara weir and Finchaa dam) have been constructed in the Ethiopian part of the catchment (Table 14.2). These two dams were built primarily to provide hydropower. They regulate flow from Lake Tana and the Finchaa River, respectively. The combined capacity of the power stations they serve (218 MW) represented approximately 13 per cent of the total installed generating capacity of the country in 2009 (i.e. 1618 MW, of which 95% was hydropower). In 2010, a new power station on the Beles River came on line (see below) and the total installed capacity increased to 1994 MW.

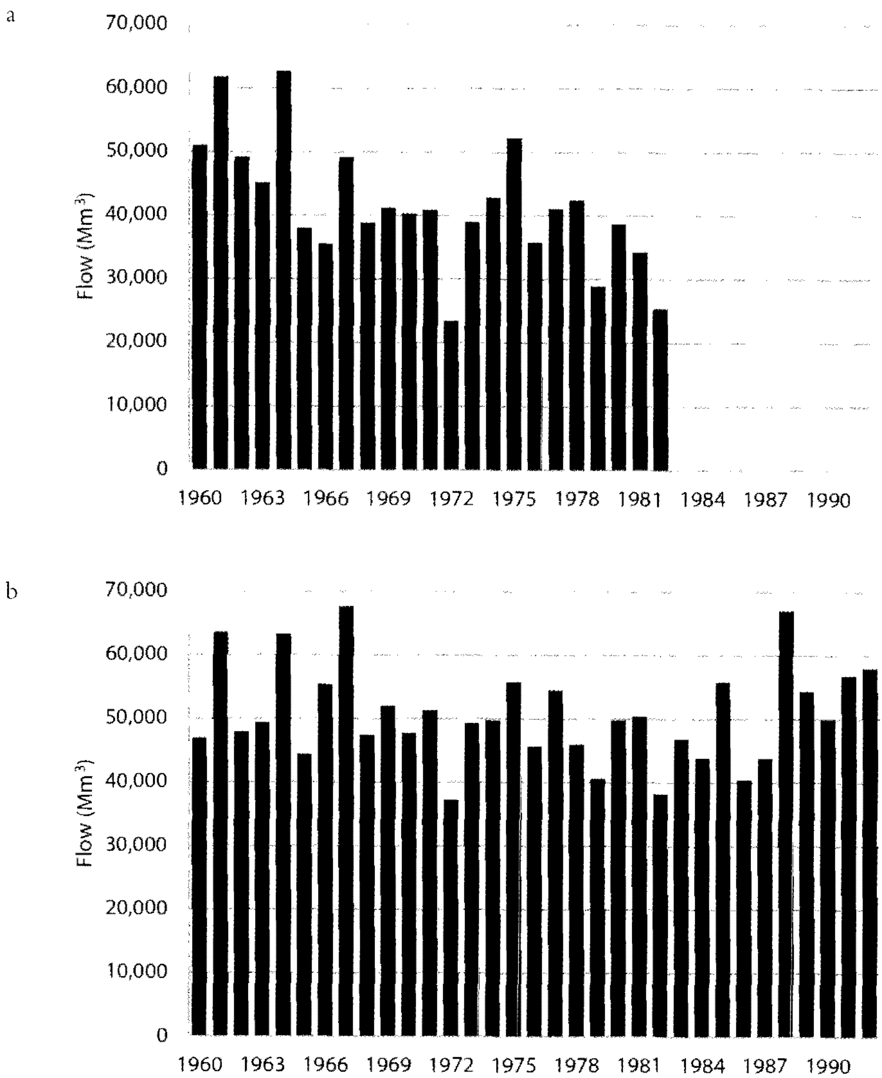


Figure 14.2 Annual flow of the Blue Nile measured at (a) Khartoum (1960–1982) and (b) the Ethiopia–Sudan border (1960–1992)

Source: Data obtained from the Global Data Runoff Centre and Ethiopian Ministry of Water Resources

Agriculture, which is the main occupation of the inhabitants in the basin, is primarily rain-fed 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 (8145 ha), which utilizes water after it has passed through the Finchaa hydropower plant (Table 14.2).

In contrast to Ethiopia, Sudan utilizes significant volumes of Blue Nile water for both irrigation and hydropower production. Two dams (i.e. Roseires and Sennar), constructed on the

Table 14.1 Mean monthly flow (million m³) and run-off (mm) measured at gauging stations located on the main stem and major tributaries of the Blue Nile River

Location		*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Annual*
Main stem														
Lake Tana	Flow	203	127	94	70	49	45	114	434	906	861	541	332	3776
	run-off	13	8	6	5	3	2	7	28	59	56	35	22	247
Kessie	Flow	331	221	227	211	209	258	3003	6594	3080	1456	788	503	16,881
	run-off	5	3	4	3	3	4	46	100	47	22	12	8	257
Border	Flow	949	545	437	359	446	1175	6293	15,502	13,068	7045	3105	1709	50,632
	run-off	5	3	2	2	2	6	31	78	65	35	16	9	253
Khartoum	Flow	724	448	406	427	503	1084	4989	15,237	13,625	7130	2451	1257	48,281
	run-off	3	2	2	2	2	4	18	55	50	26	9	5	176
Major tributaries														
Besheilo	Flow	4	4	4	5	5	14	494	1303	527	74	19	9	2462
	run-off	0.3	0.3	0.3	0.4	0.4	1	37	98	40	6	1	0.6	186
Welaka	Flow	2	2	2	3	3	7	261	689	279	39	10	5	1302
	run-off	0.3	0.3	0.4	0.4	0.4	1	41	107	44	6	2	0.7	203
Jemma	Flow	6	5	6	7	7	18	662	1748	707	100	25	11	3301
	run-off	0.4	0.3	0.4	0.4	0.5	1	42	111	45	6	2	0.7	209
Muger	Flow	1	1	1	2	2	6	268	753	312	44	10	4	1402
	run-off	0.1	0.1	0.1	0.2	0.2	0.7	33	92	38	5	1	0.5	171
Guder	Flow	0	0	0	0	0	7	43	66	50	15	1	0	182
	run-off	0	0	0	0	0	1	6	9	7	2	0.1	0	26
Finchaa	Flow	45	29	21	18	16	20	108	347	464	409	220	91	1786
	run-off	11	7	5	4	4	5	26	85	113	100	54	22	437
Anger	Flow	44	25	21	22	37	114	386	717	716	436	141	75	2733
	run-off	6	3	3	3	5	14	49	91	91	55	18	10	346
Didessa	Flow	109	62	52	54	93	283	958	1782	1779	1084	352	186	6791
	run-off	6	3	3	3	5	14	49	91	91	55	18	10	346
Wombera	Flow	72	41	34	35	61	187	632	1176	1174	715	233	123	4483
	run-off	6	3	3	3	5	14	49	91	91	55	18	10	346
Dabus	Flow	306	155	114	88	94	214	534	917	1336	1460	1070	602	6888
	run-off	15	7	5	4	5	10	25	44	64	69	51	29	328
North Gojam	Flow	6	5	6	8	8	20	730	1927	779	110	27	13	3639
	run-off	0.4	0.4	0.4	0.5	0.5	1	51	134	54	8	2	1	253
South Gojam	Flow	7	6	7	9	9	24	855	2257	913	128	32	15	4262
	run-off	0.4	0.4	0.4	0.5	0.6	1.4	51	135	54	8	2	1	254
Beles	Flow	6	2	2	1	2	36	393	846	637	218	42	12	2195
	run-off	0.4	0.1	0.1	0	0.2	3	28	60	45	15	3	1	155
Rahad	Flow	0	0	0	0	0	1	132	342	354	201	26	1	1056
	run-off	0	0	0	0	0	0.1	16	41	43	24	3	0.1	128
Dinder	Flow	0	0	0	0	0	17	291	968	917	376	34	4	2609
	run-off	0	0	0	0	0	1	20	65	62	25	2	0.2	176

Source: BCEOM (1998), with slight modifications based on more recent feasibility studies of ENTRO (2007) and Sutcliffe and Parks (1999)

main river approximately 350 and 620 km southeast of Khartoum (Table 14.2), provide hydropower (primarily for Khartoum) as well as water for several large irrigation schemes. These include the Gezira irrigation 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

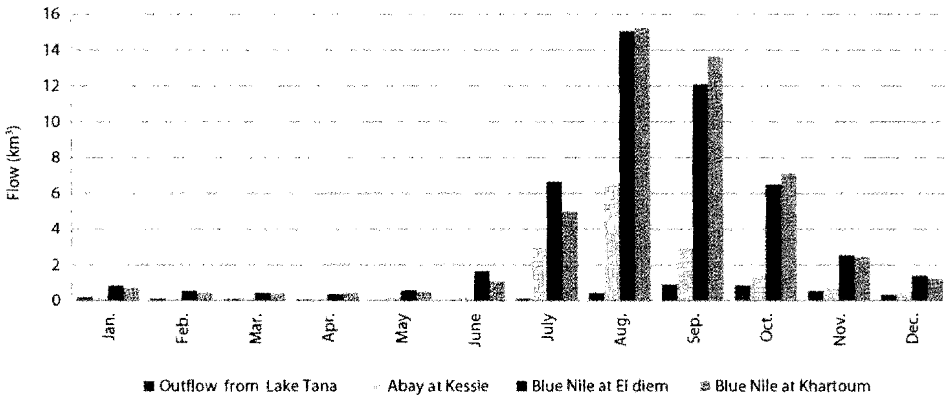


Figure 14.3 Mean monthly flow (million m³) at gauging stations located on the main stem of the Blue Nile

Source: Data provided by the Ministry of Water Resources, Ethiopia and the UNESCO Chair in Water Resources, Sudan

irrigated area in the Sudanese part of the Blue Nile is estimated to be 1,305,000 ha, consisting of a variety of crops including cotton, sugar cane and vegetables. The installed power capacity at the two dams is 295 MW, which represents 25 per cent of the country's total generating capacity (i.e. 1200 MW from both thermal and hydropower stations).

Table 14.2 Existing dams in the Blue Nile catchment

Dam	*Country*	*River*	*Storage (million m³)*	*Year dam was built*	*Purpose*
Chara Chara	Ethiopia	Abay	9100[a]	2000	Regulation of Lake Tana outflows for hydropower production at Tis Abay I and Tis Abay II power stations (installed capacity 84 MW) and, since 2010, for transfer of water to the Beles River hydropower station (installed capacity 460 MW)
Finchaa[b]	Ethiopia	Finchaa	2395	1971	Regulation for hydropower production (installed capacity 134 MW) and also for irrigating sugar cane plantations (8145 ha)
Roseires	Sudan	Blue Nile	3024	1964	Regulation for hydropower production (installed capacity 280 MW) and for supply to irrigation schemes (1,305,000 ha)
Sennar	Sudan	Blue Nile	930	1925	Regulation for hydropower production (installed capacity 15 MW) and for supply to irrigation schemes (1,093,502 ha)

Notes: [a] This is the active storage of Lake Tana that is controlled by the operation of the weir (i.e. lake levels between 1784 and 1787 masl). It represents 2.4 times the average annual outflow of the lake

[b] There is a small dam located on the Amerty River (storage 40 million m³), which diverts water from the Amerty River into the Finchaa reservoir

Future water resources development

Both Ethiopia and Sudan contend that utilization of the Nile water resources is essential for socio-economic development and poverty alleviation. Consequently, both countries are planning significant development of the Blue Nile River water resources in the future.

In Ethiopia, current planning is focused primarily on the Lake Tana and the Beles River catchments which have been identified by the government as an economic 'growth corridor' (McCartney *et al.*, 2010). However, additional projects are planned in nearly all the sub-catchments as well as along the main river. Possible irrigation projects have been investigated over a number of years (e.g. Lahmeyer, 1962; USBR, 1964; JICA, 1977; WAPCOS, 1990; 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 Ethiopian Blue Nile, more than 120 potential hydropower sites have been identified (WAPCOS, 1990). Of these, 26 were investigated in detail during the preparation of the Abay River Basin Master Plan (BCEOM, 1998). The major hydropower projects currently being contemplated in Ethiopia have a combined installed capacity of between 3634 and 7629 MW (cf. the Aswan High Dam, which has an installed capacity of 2100 MW). The exact value depends on the final design of the dams and the consequent head that is produced at each. The four largest schemes being considered are dams on the main stem of the Blue Nile River. Of these schemes the furthest advanced is the Karadobi project for which the pre-feasibility study was conducted in 2006 (Norconsult, 2006).

In addition to the single-purpose hydropower schemes, electricity generation is expected to be added to several of the proposed irrigation projects where dams are being built. This is estimated to provide an additional 216 MW of capacity (BCEOM, 1998). The total energy produced by all the hydropower schemes being considered is in the range 16,000–33,000 GWh yr^{-1}. This represents 20 to 40 per cent of the technical potential in the Ethiopian Blue Nile (i.e. 70,000 GWh yr^{-1}) estimated by the Ministry of Water Resources (Beyene and Abebe, 2006). Currently, it is anticipated that much of the electricity generated by these power stations will be sold to Sudan and possibly to other countries in the Nile Basin.

Sudan is also planning to increase the area irrigated in the BNB. Additional new projects and extension of existing schemes are anticipated to add an additional 889,340 ha by 2025. An additional 4000 million m^3 of storage will be created by raising the height of the existing Roseries dam by 10 m (Omer, 2010). However, currently there are no plans for additional dams to be constructed on the Blue Nile.

Technically feasible hydropower energy production in the Nile Basin of Sudan is estimated to be 24,137 GWh yr^{-1} (Omer, 2009), most of which is on the main Nile downstream of the White and Blue Nile confluence. Currently, the Merowe dam, with an installed capacity of 2500 MW, is being commissioned on the Nile downstream of Khartoum. Several other major hydropower dams are being planned, none of which are to be located on the Blue Nile River.

Application of the Water Evaluation And Planning model

Model description

Developed by the Stockholm Environment Institute (SEI), the WEAP model is intended to be used to evaluate planning and management issues associated with water resources development. The WEAP model essentially calculates 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, wastewater treatment facilities; and water demands (i.e. user-defined sectors, but typically comprising industry, mines, irrigation and domestic supply; Yates *et al.*, 2005; SEI, 2007).

Typically, the model is 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. For each scenario, 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. All demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 the lowest. 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 configured to simulate the 16 major sub-catchments of the basin (Figure 14.4a). It was assumed that because hydropower generates greater income it would be considered more important than irrigation by both governments. Consequently, within WEAP it was given a higher priority than irrigation. However, all schemes in Ethiopia and Sudan were given the same priority (i.e. no attempt was made to reflect differences between upstream and downstream locations).

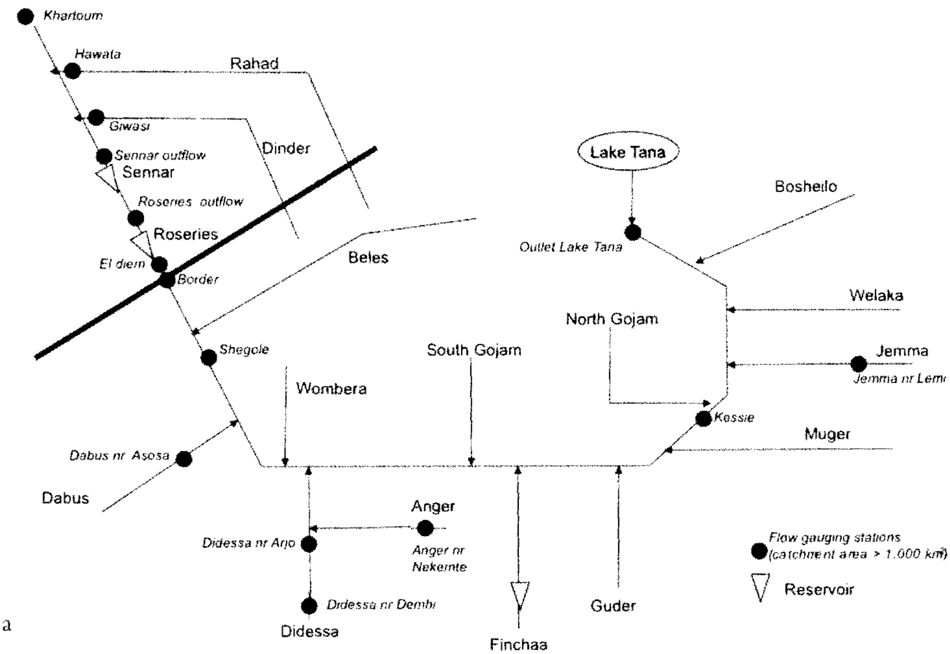
Description of the scenarios

Scenarios are commonly used to investigate complex systems that are inherently unpredictable or insufficiently understood to enable precise predictions. In this instance, although there is reasonable (but not total) knowledge of current (i.e. 2008) water demand, there is considerable uncertainty about how future water resources development will proceed. Consequently, a scenario approach was adopted.

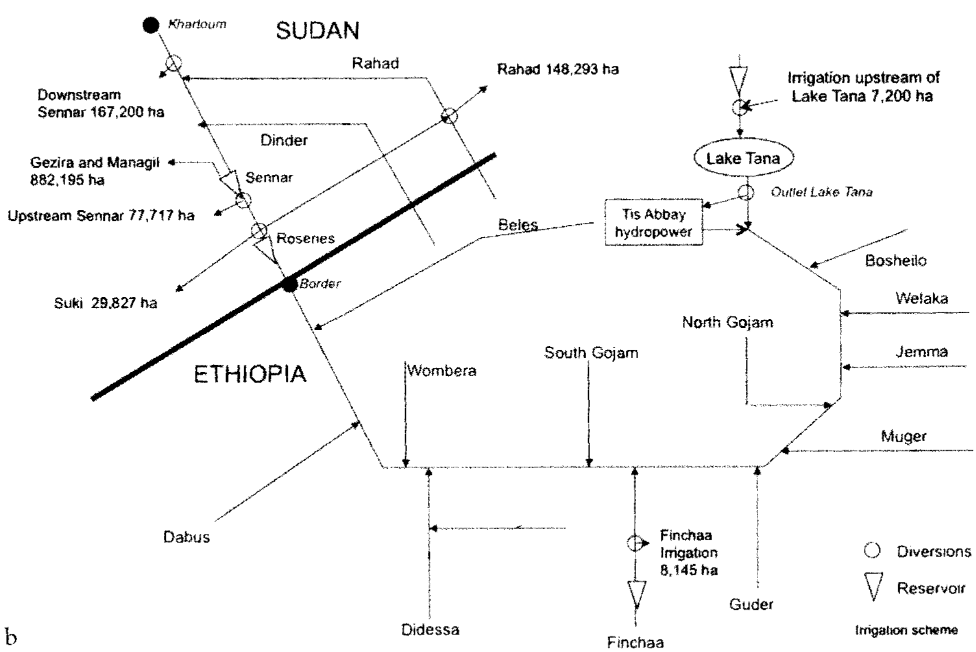
The model was set up to simulate four scenarios, each of which provides a coherent, internally consistent and plausible description of water demand within the catchment (Table 14.3; Figure 14.4a–d).

Table 14.3 Water resources development scenarios simulated using the Water Evaluation And Planning model

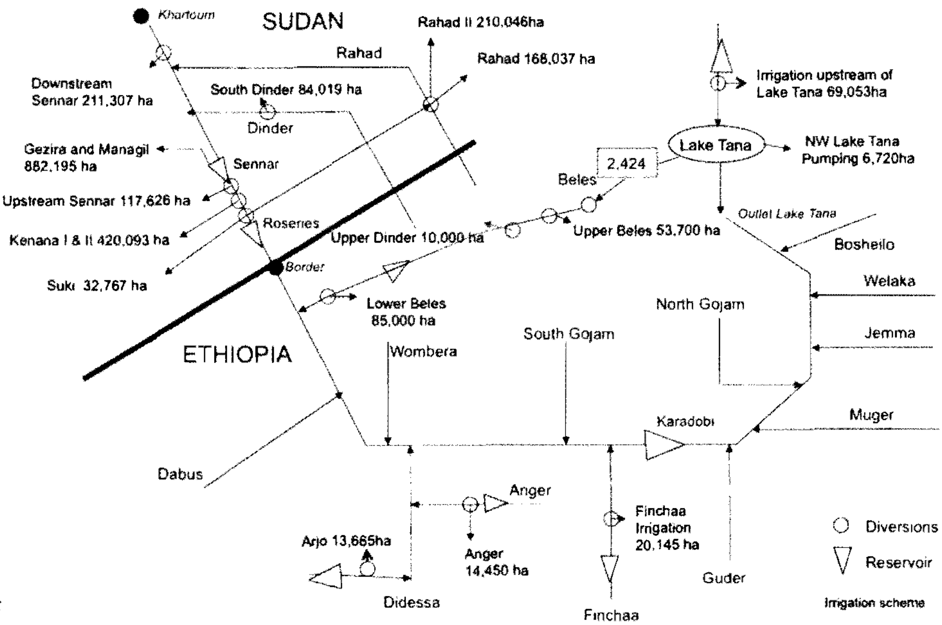
Scenario	*Description*
Natural	No human-made storage and no abstractions so that flows are assumed to be natural. This scenario provides a 'baseline' against which all the other scenarios can be assessed.
Current	The current water resources development situation (around 2008) including all major irrigation and hydropower schemes.
Medium-term future	Water resources development (irrigation and hydropower) in the medium-term future (around 2010–2025) including all schemes for which feasibility studies have been conducted.
Long-term future	Water resources development (irrigation and hydropower) in the long-term future (around 2025–2050) including schemes that are included in basin master plans, but have not yet reached the feasibility study stage of planning.


Khartoum
Hawata
Rahad
Giwasi
Dinder
Sennar outflow
Sennar
Roseries outflow
Roseries
El diem
Border
Beles
Shegole
Lake Tana
Outlet Lake Tana
Bosheilo
Welaka
North Gojam
South Gojam
Jemma
Jemma nr Lemi
Wombera
Kessie
Muger
Dabus nr Asosa
Dabus
Anger
Didessa nr Arjo
Anger nr Nekemte
Flow gauging stations (catchment area > 1,000 km²)
Reservoir
Didessa nr Dembi
Guder
Didessa
Finchaa

a


Khartoum
SUDAN
Rahad
Rahad 148,293 ha
Irrigation upstream of Lake Tana 7,200 ha
Downstream Sennar 167,200 ha
Dinder
Gezira and Managil 882,195 ha
Sennar
Lake Tana
Outlet Lake Tana
Upstream Sennar 77,717 ha
Tis Abbay hydropower
Beles
Roseries
Bosheilo
Border
Suki 29,827 ha
Welaka
North Gojam
South Gojam
Jemma
ETHIOPIA
Wombera
Muger
Dabus
Finchaa Irrigation 8,145 ha
Diversions
Reservoir
Guder
Didessa
Finchaa
Irrigation scheme

b



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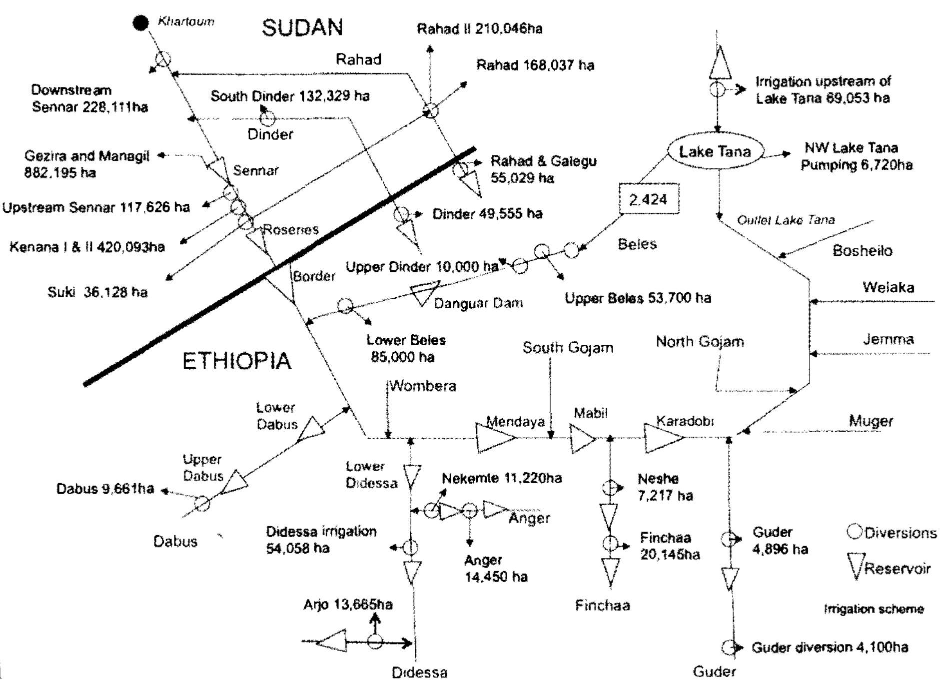

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Figure 14.4 Schematic of the model configuration for different scenarios: (a) the natural situation, (b) the current (2008) situation, (c) the medium-term (2010–2025) future, and (d) the long-term (2025–2050) future

Time series of monthly naturalized flow data for the period 1960–1992, obtained from the Abay Basin Master Plan (BCEOM, 1998), and modified slightly based on more recent feasibility studies (ENTRO, 2007), were used as input data. In the future scenarios, considerable time is needed to fill the planned large reservoirs, particularly those located on the main stem of the Blue Nile River. Hence, a 20-year 'warm-up' period was introduced and all comparisons between scenarios were made for just the 13 years 1980–1992.

Estimates of current irrigation and hydropower demand were derived from data provided by government ministries and agencies or from previous studies. These included information on water passing through the turbines of the power stations and water diverted for irrigation. It was necessary to make several assumptions, particularly about irrigation demands and the return flows from irrigation schemes. Net evaporation from Lake Tana and the reservoirs was estimated from rainfall and potential evaporation data obtained from the meteorological station located closest to each dam. These data were obtained from the FAO LocClim database (FAO, 2002).

For the medium-term and long-term scenarios, the sizes of planned hydropower and irrigation development schemes were derived from the basin master plan for the Ethiopian Blue Nile and through discussion with academics and water resource planners in Sudan. New schemes, proposed extension of existing irrigation schemes as well as planned hydropower developments were identified (Tables 14.4 and 14.5). The medium-term scenario includes the Tana–Beles transfer scheme in Ethiopia. This project, which involves the transfer of water from Lake Tana to the Beles River to generate hydropower, actually came on line in 2010, but after the modelling had been undertaken (McCartney *et al.*, 2010).

Table 14.4 Proposed irrigation development in the Blue Nile River Basin

Scheme	*Sub-basin*	*Description*	*Estimated completion date*
Ethiopia			
Lake Tana	Lake Tana	Dams to be constructed on the major inflows to Lake Tana (i.e. Megech, Ribb, Gumara and Gilgel Abay) Total storage: 1028 million m^3 Irrigation area: 61,853 ha Average annual demand: 516 million m^3	Medium term
Beles	Beles	Upper Beles scheme: 53,700 ha Lower Beles scheme: 85,000 ha Average annual demand: 1554 million m^3	Medium term
Anger	Anger	Maximum irrigated area: 14,450 ha Average annual demand: 202 million m^3	Medium term
Arjo	Didessa	Arjo scheme: 13,665 ha Average annual demand: 92.1 million m^3	Medium term
Dinder	Dinder (but water transferred from Beles)	Upper Dinder scheme: 10,000 ha Average annual demand: 98.2 million m^3	Medium term
Finchaa	Finchaa	Extension of existing scheme Additional area: 12,000 ha Average annual demand: 456.6 million m^3	Medium term

Table 14.4 Continued

Scheme	*Sub-basin*	*Description*	*Estimated completion date*
Rahad and Galegu	Rahad	Rahad and Galegu scheme: 15,029 ha Average annual demand: 607 million m^3	Long term
Dinder	Dinder	Dinder scheme: 49,555 ha Average annual demand: 556 million m^3	Long term
Guder	Guder	Guder diversion: 4100 ha Guder: 4896 ha Average annual demand: 54.4 million m^3	Long term
Nekemte	Anger	Nekemte scheme: 11,220 ha Average annual demand: 71.5 million m^3	Long term
Didessa	Didessa	Didessa irrigation scheme: 54,058 ha Average annual demand: 769.4 million m^3	Long term
Sudan			
Raising Roseries Dam	Blue Nile main stem	Roseries dam raised by 10 m to provide total (gross) storage of 7400 million m^3.	Medium term
Extension of Rahad irrigation scheme	Rahad	Additional irrigation area: 19,740 ha Rahad II irrigation scheme: 210,000 ha Total average annual demand: 2433 million m^3	Medium term
Extension of Suki irrigation scheme	Blue Nile main stem	Additional irrigation area: 2940 ha/3361 ha Total average annual demand: 201 million m^3/221 million m^3	Medium/ long term
Extension of Upstream Sennar	Blue Nile main stem	Additional irrigation area: 39,910 ha Total average annual demand: 745 million m^3	Medium term
Extension of Downstream Sennar	Blue Nile main stem	Additional irrigation area: 44,110 ha/6804 ha Total average annual demand: 1414 million m^3/ 1526 million m^3	Medium/ long term[a]
Kenana II and III	Blue Nile main stem	Additional irrigation area: 420,093 ha Average annual demand: 2352 million m^3	Medium term
South Dinder	Dinder	Additional irrigation area: 84,019 ha/48,318 ha[b] Average annual demand: 541 million m^3/851 million m^3[b]	Medium/ long term

Notes: [a] Schemes are extended partially in the medium-term future and partially in the long-term future
[b] The slash in the third column demarcates values between the medium-term future and the long-term future

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. For the Sudanese schemes, information on likely completion dates was obtained

Table 14.5 Proposed hydropower development in the Blue Nile River Basin

Scheme	*Sub-basin*	*Description*	*Estimated completion date*
Ethiopia			
Tana–Beles	Tana and Beles	Transfer of water from Lake Tana to Beles catchment for hydropower production and irrigation Hydropower capacity: 460 MW Average annual transfer: 2424 million m^3	Medium term
Anger	Anger	Linked to the Anger irrigation scheme Hydropower capacity: 1.8–9.6 MW	Medium term
Arjo	Didessa	Linked to the Arjo irrigation scheme Hydropower capacity: 33 MW	Medium term
Karadobi	Blue Nile main stem	Height of dam: 250 m Total storage: 40,220 million m^3 Hydropower capacity: 1600 MW	Medium term
Mendaya	Blue Nile main stem	Height of dam: 164 Total storage: 15,900 million m^3 Hydropower capacity: 1620 MW	Medium term
Border	Blue Nile main stem	Height of dam: 90 m Total storage: 11,100 million m^3 Hydropower capacity: 1400 MW	Long term
Mabil	Blue Nile main stem	Height of dam: 170 m Total storage: 17,200 million m^3 Hydropower capacity: 1200 MW	Long term
Lower	Didessa	Didessa Height of dam: 110 m Total storage: 5510 million m^3 Hydropower capacity: 190 MW	Long term
Dabus	Dabus	Linked to the Dabus irrigation scheme. Hydropower capacity: 152 MW	Long term
Danguar	Beles	Height of dam: 120 m Total storage: 4640 million m^3 Hydropower capacity: 33 MW	Long term
Lower	Dabus	Dabus Height of dam: 50 m Total storage: 1290 million m^3 Hydropower capacity: 164 MW	Long term

from discussions with water resources experts within the country. 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 water withdrawals for irrigation schemes were derived from a variety of sources, including the Ethiopia Basin master plan and, where available, feasibility studies. For Sudan, useful information on irrigation water use was obtained from a study of the Roseries irrigation scheme (Ibrahim *et al.*, 2009). In schemes for which there were no data, it was assumed that withdrawals per hectare would be similar to those at the nearest scheme where data were available, with some allowances for differences in rainfall where this differed significantly between locations. Irrigation return flows were estimated from existing feasibility studies, and averaged approximately 20 per cent of withdrawals in Ethiopia and 15 per cent in Sudan. Where it is planned to extend irrigation schemes the future withdrawals and return flows were estimated based on current values but weighted by the new area. Thus, no allowance was made for possible future improvements in irrigation efficiency. Furthermore, no allowance was made for inter-annual variations in rainfall, which might affect irrigation demand between years.

Results

Model validation

Figure 14.5 shows the simulated and observed flows at the Ethiopia–Sudan border and at Khartoum for the current situation. At Khartoum, observed data (obtained from the Global Data Runoff Centre) were only available for the period 1960–1982. Over this period the error in the simulated mean annual flow was 1.9 per cent. As a result of current abstractions, primarily for irrigation in Sudan, the flow at Khartoum is estimated to be approximately 7.8 billion m^3 yr^{-1} less than would have occurred naturally over this period (i.e. 42.4 billion m^3 yr^{-1} rather than 50.2 billion m^3 yr^{-1}). At the border there are two flow gauging stations. One is operated by the Government of Ethiopia, and just a few kilometres 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 per cent difference in mean annual flow over the period 1960–1992: 50.6 billion m^3 measured by Ethiopia and 45.5 billion m^3 measured by Sudan. Without a 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 falls between the two with a mean annual discharge of 46.2 billion m^3.

Figure 14.6 compares the simulated and observed water levels of Lake Tana, also over the period 1960–1992. Although the average simulated water level (1786.3 masl) is close to the observed average (1786.0 masl), it is clear that the variability in the simulated water levels does not quite match that of the observed levels. Nevertheless, these results in conjunction with the flow results indicate that the WEAP simulation of the current situation is reasonably accurate and provides credibility for the results of the simulated future scenarios.

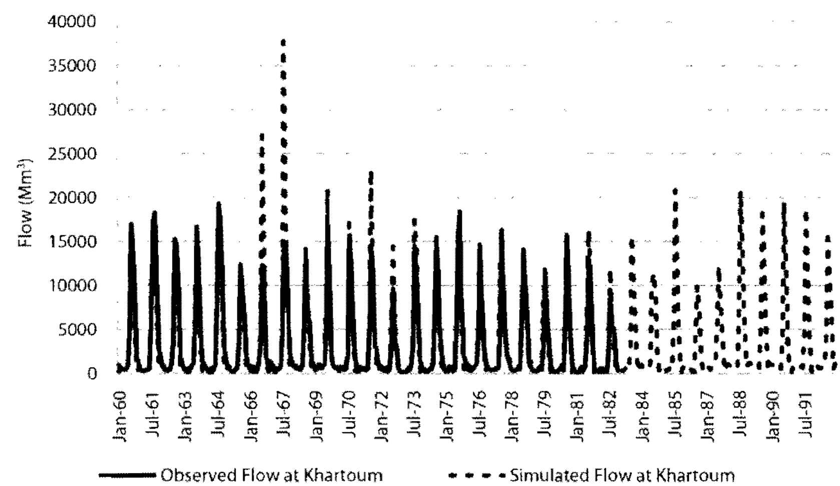
Comparison of scenarios

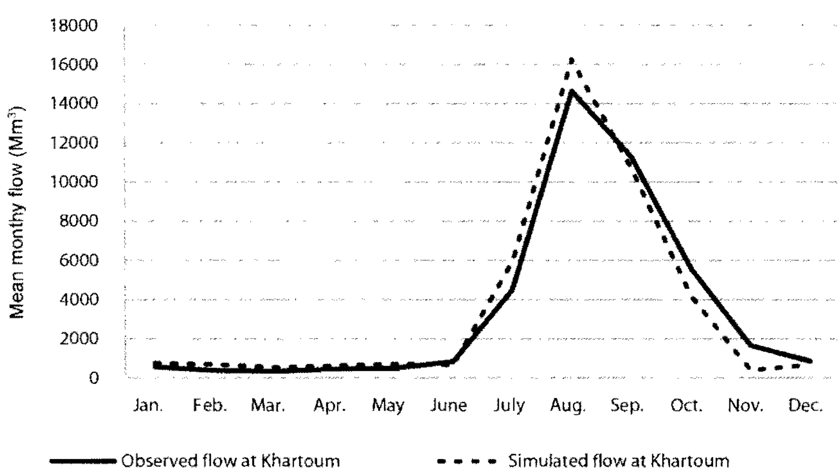
Currently, irrigation water withdrawals in Sudan greatly exceed those in Ethiopia because of the differences in irrigated area. The total irrigation demand in Sudan is estimated to average 8.45 billion m^3 yr^{-1}. This compares with an average of just 0.26 billion m^3 yr^{-1} in Ethiopia. With the planned irrigation development, demand is estimated to increase to 13.39 billion and 2.38 billion m^3 yr^{-1} in the medium-term scenarios, and to 13.83 billion and 3.81 billion m^3 yr^{-1} in the long-term scenarios in Sudan and Ethiopia, respectively (Table 14.6). If all planned dams are constructed the total reservoir storage in Ethiopia is estimated to increase to 70 billion m^3 (i.e. 1.5 times the mean annual flow at the border) in the mid-term and to 167 billion m^3 (i.e.

3.6 times the mean annual flow at the border) in the long term. Hydropower generated in Ethiopia, from the Tis Abay and Finchaa power stations, is currently estimated to be 1383 GWh yr^{-1}. With the construction of the Tana Beles transfer, the Karadobi dam and other smaller schemes, this is estimated to increase to 12,908 GWh yr^{-1} in the medium term. With Border, Mendaya and Mabil hydropower stations, as well as with additional smaller schemes, electricity production in the long term could increase to 31,297 GWh yr^{-1}.

Hydropower generated on the Blue Nile in Sudan is currently estimated to be just over 1000 GWh yr^{-1}, but there are no publicly available data to confirm this estimate. Because of the additional head and increased storage, the raising of the Roseries dam will result in a very small increase to 1134 GWh yr^{-1} in the medium term and to 1205 GWh yr^{-1} in the long term. The increase in the long term is due entirely to greater dry season flows, resulting from increased regulation upstream in Ethiopia.

a





b

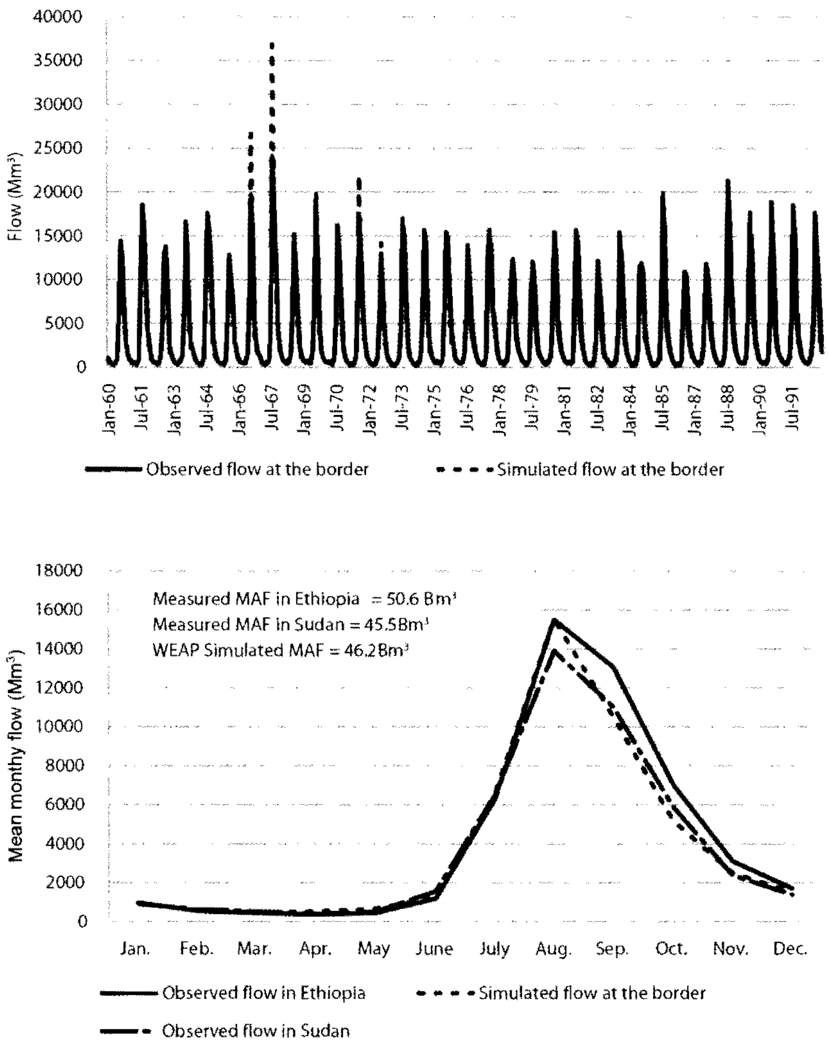


Figure 14.5 Simulated and observed flow series and mean monthly flows (1960–1992) for the Blue Nile (current situation) at (a) Khartoum and (b) the Ethiopia–Sudan border

Comparison of the mean monthly flows at Khartoum for the simulated natural condition, current situation and the medium- and long-term scenarios, for the 13 years 1980–1992, indicates how the mean annual flow is progressively reduced as a consequence of greater upstream abstractions (Table 14.7). Wet season flows are reduced significantly, but dry season flows are increased as a consequence of flow regulation (Figure 14.7; Table 14.7). Under natural conditions, 84 per cent of the river flow occurs in the wet season months (July–October). In the medium-term and long-term scenarios this is reduced to 61 and 37 per cent, respectively.

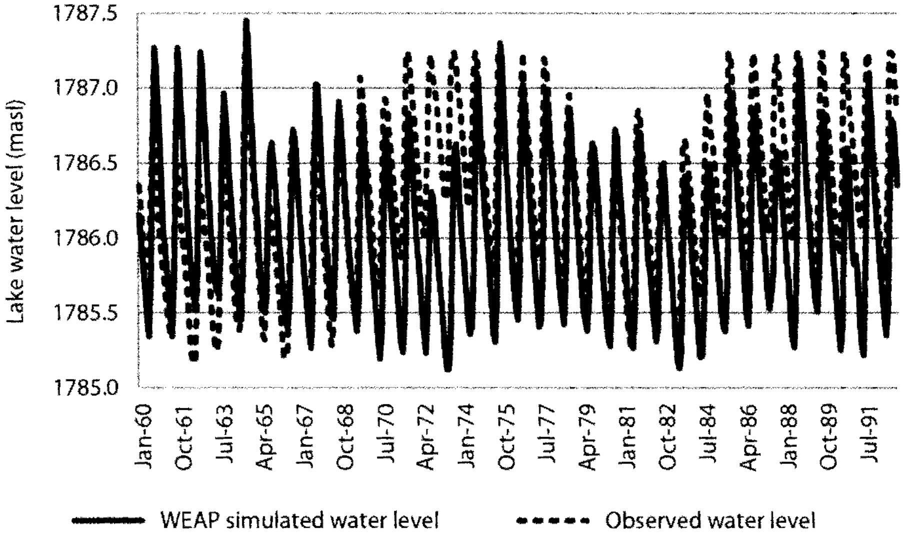


Figure 14.6 Simulated and observed water levels in Lake Tana (1960–1992)

Table 14.6 Comparison of current and future irrigation demand and hydropower production in the Ethiopian and Sudanese parts of the Blue Nile

	Current		*Medium-term future*		*Long-term future*	
	Ethiopia	*Sudan*	*Ethiopia*	*Sudan*	*Ethiopia*	*Sudan*
Total storage (million m^3)	11,578	3370[a]	70,244	10,770	167,079	10,770
Formal irrigation						
Area (ha)	<10,000	1,305,000	210,000	2,126,000	461,000	2,190,000
Water withdrawals per year (million m^3 yr^{-1})	0.26	8.45	2.38	13.39	3.81	13.83
Hydropower						
Installed capacity (MW)	218	295	2194	295	6426	295
Production (GWh yr^{-1})	1383	1029	12,908	1134	31,297	1205

Note: [a] Allowance made for sedimentation of both the Roseries and Sennar reservoirs

At the Ethiopia–Sudan border the current situation is almost identical to the natural condition, so this is not shown (Figure 14.7). Mean annual flow is reduced from 45.2 to 43.2 and 42.7 billion m^3 in the medium-term and long-term future scenarios, respectively. As in Khartoum, there is a significant reduction in wet season flows, but there are significant increases in dry season flows as a consequence of flow regulation (Figure 14.7; Table 14.7). Under natural conditions 81 per cent of the river flow occurs in the wet season, but this decreases to 59 and 43 per cent in the medium-term and long-term scenarios, respectively. The total decrease in border flow in the long-term scenario is less than might be expected given the increased

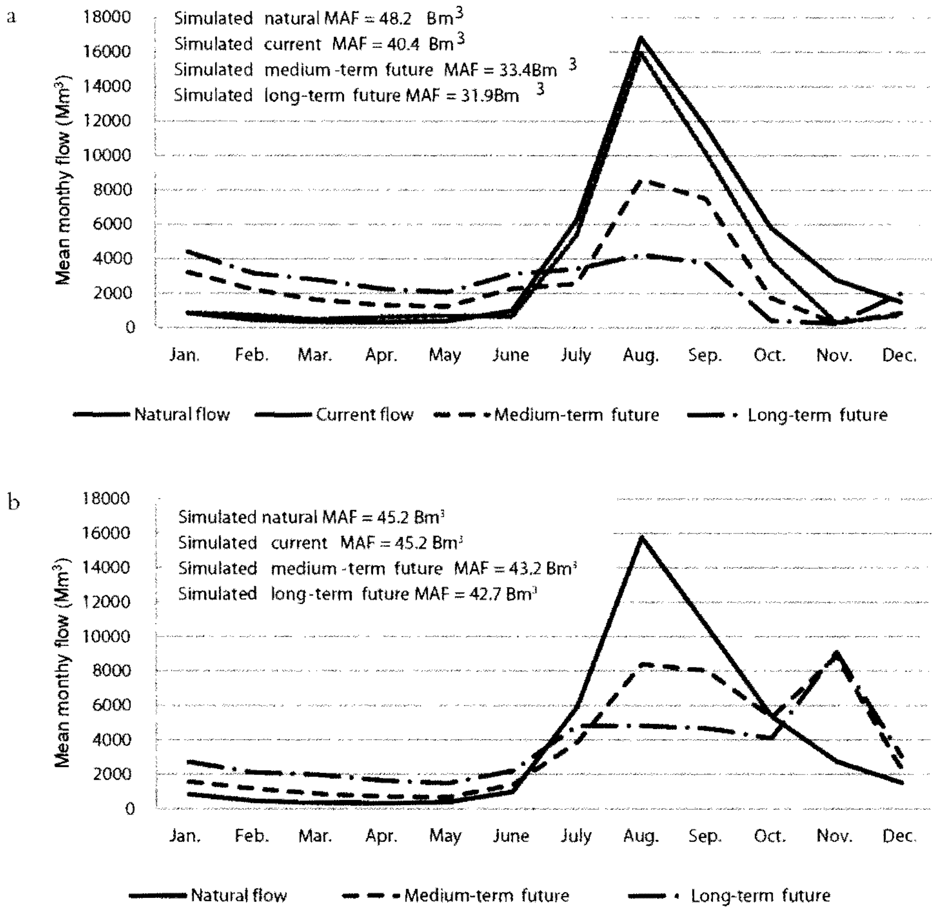


Figure 14.7 Comparison of simulated mean monthly flow derived for natural, current, medium-term and long-term future scenarios at (a) Khartoum and (b) the Ethiopia–Sudan border

irrigation demand in Ethiopia. The reason is partly that less water is diverted from the Tana to the Beles catchment and more flow is routed down the main stem of Blue Nile.

Currently, shortfalls (i.e. failure in any given month to supply the full amount of water needed for irrigation withdrawals or hydropower needs) in Ethiopia are negligible. However, in the medium-term scenario shortfalls increase to 0.8 and 5.0 billion m^3 yr^{-1} for irrigation and hydropower, respectively. In the long term, the increased storage means that shortfalls will average 0.4 billion m^3 yr^{-1} for irrigation and 0.7 billion m^3 yr^{-1} for hydropower. In comparison, under current conditions, there is an average shortfall of 0.8 billion m^3 yr^{-1} in water for the Sudanese irrigation schemes. However, because of the improved flow regulation there are no shortfalls in irrigation or hydropower in Sudan in either the medium- or the long-term scenarios. These results reflect the fact that, in each scenario, the Sudanese schemes were given the same priority as those in Ethiopia. Hence, although in the medium term and long term more water is stored in Ethiopia, in these scenarios, no preference was given to the schemes in Ethiopia.

Table 14.7 Simulated mean monthly flow (million m^3) at the Ethiopia–Sudan border and Khartoum for natural, current, medium- and long-term future scenarios (1980–1992)

Month	*Natural*		*Current*		*Medium-term future*		*Long-term future*	
	Border	*Khartoum*	*Border*	*Khartoum*	*Border*	*Khartoum*	*Border*	*Khartoum*
January	835	835	955	855	1565	3220	2710	4405
February	470	470	580	740	1180	2220	2110	3175
March	350	350	400	475	845	1615	1980	2770
April	310	310	520	620	710	1315	1635	2250
May	390	390	645	710	680	1235	1485	2055
June	980	990	1230	640	1390	2275	2205	3125
July	5930	6235	6105	5365	3870	2560	4820	3420
August	15,770	16,830	15,430	15,950	8400	8615	4820	4245
September	10,590	11,680	10,130	10,165	8020	7490	4665	3760
October	5360	5825	4970	3865	5315	1740	4105	420
November	2750	2795	2615	310	8870	260	9095	250
December	1510	1510	1575	740	2305	850	3055	1990
Total	45,245	48,220	45,155	40,435	43,150	33,395	42,685	31,865

Net evaporation (i.e. the difference between evaporation from a reservoir and the rainfall directly onto its surface) from the Ethiopian reservoirs currently averages 0.8 billion m^3 yr^{-1}. However, by far the bulk of this is from Lake Tana which is a natural geographic feature and would be evaporating even without regulation. By comparison, net evaporation from the Sudanese reservoirs is 0.4 billion m^3 yr^{-1}. In the medium term this increases to 1.2 billion m^3 yr^{-1} in Ethiopia (0.3 billion m^3 yr^{-1} excluding Lake Tana) and to 1.4 billion m^3 yr^{-1} in Sudan. The increase in Sudan is due to the increased area of the Roseries reservoir arising from raising the Roseries Dam and the fact that water levels in both Roseries and Sennar reservoirs are maintained at higher levels because of the higher dry season inflows. In the long term, total net reservoir evaporation increases to 1.7 billion m^3 yr^{-1} in Ethiopia (0.8 billion m^3 yr^{-1} excluding Lake Tana) and remains at 1.4 billion m^3 yr^{-1} in Sudan. However, evaporation losses per cubic metre of water stored are considerably lower in Ethiopia than in Sudan in all the scenarios. In fact, as a result of the locations of the planned reservoirs, as storage increases in Ethiopia, losses per cubic metre of water stored decrease significantly over time (Table 14.8).

Table 14.8 Simulated average annual net evaporation from reservoirs in Ethiopia and Sudan for each of the scenarios

Scenario	*Ethiopia*[a]			*Sudan*		
	Total storage (million m^3)	*Total evaporation (million m^3)*	*Evaporation from storage (m^3 m^{-3})*	*Total storage (million m^3)*	*Total evaporation (million m^3)*	*Evaporation from storage (m^3 m^{-3})*
Current	11,578	846	0.07	3370	443	0.13
Medium term	70,244	1158	0.02	10,770	1363	0.13
Long term	167,079	1732	0.01	10,770	1387	0.13

Notes: [a] Including from Lake Tana, which is a natural lake, though regulated by the Chara Chara weir

Discussion

The results presented in this chapter are based on many assumptions. Lack of data on flow and water demand and use, particularly in Sudan, makes it very difficult to validate the model for the current situation. However, where it has been possible to verify them the model results appear to be reasonably accurate. For example, in the current scenario, simulated flows closely match the observed flows at key locations on the main stem of the river and the simulated water levels in Lake Tana were reasonably accurate (Figures 14.5 and 14.6). Consequently, though the results should be treated with caution, they are believed to be broadly indicative of the likely impacts arising from the development currently being considered in both Ethiopia and Sudan. By illustrating what may occur the scenarios provide information that is useful for resource planning, and the results provide a basis for discussion.

Climate, and hence hydrological variability, possibly increased by future climate change, will remain key factors in the economic development of both Ethiopia and Sudan in the future. As in the past, future water resources development in the Blue Nile will be driven predominantly by the need for water for agriculture and hydropower, and hence the need for large volumes of stored water. Irrigation will remain by far the largest user of water and the future scenarios indicate significantly increased water withdrawals as a consequence of increasing irrigation, predominantly in Sudan, and also increasingly in Ethiopia. The construction of the dams, particularly the very large hydropower dams proposed by Ethiopia, though not consuming large amounts of water, will significantly alter the flow regime of the river, resulting in lower wet season flows and much greater dry season flows. The results of this are likely to be beneficial for Sudan. The frequency of flooding, which occurs every few years in the flat areas of the country and is particularly devastating in and around Khartoum, may be reduced. Higher dry season flows mean greater availability of water at a time when it is naturally scarce and hence increased opportunities for withdrawals for irrigation and other uses. Thus increased water storage in Ethiopia has the potential to provide benefits for Sudan too.

As a result of higher rainfall and lower evaporative demand, net evaporation loss per cubic metre of water stored in the Ethiopian reservoirs (including Lake Tana, which is a natural lake) is currently approximately 50 per cent of that in Sudan. As more water is stored in Ethiopia, this ratio decreases, so that in the long term it could be as low as 8 per cent of that in Sudan (Table 14.8). This confirms that one of the most significant benefits of storing water in the Ethiopian Highlands, rather than in the lower, more arid, regions of Sudan (or indeed in Egypt) is significantly reduced evaporation losses.

For all scenarios, the model was run as a single system, making no allowance for the fact that Ethiopia and Sudan are separate countries. Water demands in Sudan were given the same priority as those in Ethiopia and water was released from reservoirs in Ethiopia to meet downstream demands in Sudan. This assumes a much higher level of cooperation between the two states, in relation to both the planning and management of water resources, than at present.

Future research is needed to refine the model. Key to improving the simulations are:

- improved estimates of irrigation water demand;
- improved estimates of the dates on which schemes will become operational;
- more realistic dam operating rules;
- detailed economic, livelihood and environmental assessments of the cumulative impacts of all the proposed schemes; and
- evaluation of the possible hydrological implications of climate change.

An important issue not considered in the current model simulations is the transient stages of reservoir filling. Given the large cumulative volume of the planned reservoirs in Ethiopia, it is essential that reservoir filling is planned and managed in such a way that adverse downstream impacts, including potentially negative environmental and social impacts, are minimized. The need to give due consideration to dam operation that provides for environmental flows, to avoid degradation of riverine ecosystems, has recently been emphasized (Reitburger and McCartney, 2011).

Conclusion

The WEAP model has been configured to simulate the impacts of water resources development in the BNB. Currently, Ethiopia utilizes very little water for irrigation, but does regulate some flow for hydropower production. In contrast, Sudan uses some water for hydropower production and also abstracts large volumes for irrigation. Both countries plan to develop water resources substantially in the near future. The extent to which actual water resources development will match the plans of both countries in the long term is unclear and will depend a lot on unpredictable social and economic factors. However, in both Ethiopia and Sudan, hydropower and irrigation are widely perceived as critical to national development and, in both countries, current investment in water infrastructure is substantial and increasing. Consequently, pressures on water resources are rising and will increase substantially in the near future.

The results of this study have confirmed that, if the states cooperate effectively, mutually beneficial scenarios are possible; upstream regulation in Ethiopia reduces evaporation losses, probably reduces the frequency of flooding and provides opportunities for greatly increased water development in Sudan. However, maximizing benefits and minimizing potential adverse impacts (e.g. to the environment), especially when the large reservoirs are being filled, require much greater cooperation than currently exists between the riparian states. The key to success is the establishment of pragmatic institutional arrangements that enable the water resources of the basin to be planned and managed as a single entity (i.e. without consideration of national borders), in the most effective and equitable manner possible. It is to be hoped that such arrangements will be devised through the protracted negotiations currently under way.

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