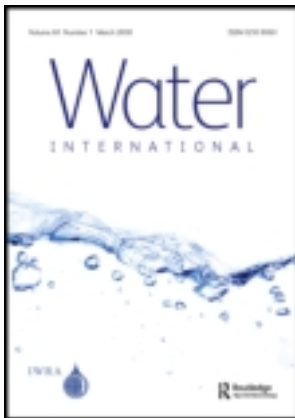


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Matthew P. McCartney^a & Michael Menker Girma^b

^a International Water Management Institute, Vientiane, Lao PDR

^b African Climate Policy Centre, United Nations Economic Commission for Africa, Addis Ababa, Ethiopia

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Evaluating the downstream implications of planned water resource development in the Ethiopian portion of the Blue Nile River

Matthew P. McCartney^{a*} and Michael Menker Girma^b

^aInternational Water Management Institute, Vientiane, Lao PDR; ^bAfrican Climate Policy Centre, United Nations Economic Commission for Africa, Addis Ababa, Ethiopia

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Ethiopia's policy of large dam construction in the Blue Nile River basin is evaluated by simulating the impact of one downscaled midrange climate change scenario (A1B) on the performance of existing and planned irrigation and hydropower schemes. The simulation finds that by 2100: 1) average basin-wide irrigation demand will increase; 2) annual hydroelectricity generation will be just 60% of potential; and 3) flow at the Ethiopia-Sudan border will be reduced from 1661 m³/s to 1301 m³/s as a consequence of climate change in combination with upstream water resource development. Adaptation to climate change and development must be considered together.

Keywords: Blue Nile; climate change; Ethiopia; hydropower; irrigation; modelling; WEAP

Introduction

The Blue Nile River is an important shared resource of Ethiopia, Sudan and also, because it is the major contributor of water to the main Nile River, Egypt. Under the auspices of the Nile Basin Initiative (NBI) the riparian countries have agreed to collaborate in principle, but formal mechanisms to develop the basin's water resources cooperatively are currently limited and tensions over water resources remain largely unresolved (Metawie 2004). Despite the significant potential benefits of regional cooperation and integrated joint basin management, all three countries continue to pursue unilateral plans for development (Cascão 2009).

Cooperation between the riparian states would be enhanced by 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 analyze the implications of different development options. A decision support system for the whole of the Nile Basin is being developed by the NBI, which it is hoped will be completed in 2012 (Beyene, Nile Basin Initiative, personal communication).

To further complicate matters, there remains great uncertainty about the likely impacts of climate change in the Blue Nile basin. The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) found that 18 of 21 global climate models (GCMs) agree in predicting increased precipitation in eastern Africa (Christensen *et al.* 2007). The AR4 therefore states that increased precipitation is "likely". However, a more recent study

*Corresponding author. Email: m.mccartney@cgiar.org

has indicated a decrease in convection and hence reduced rainfall over much of the eastern flank of the Ethiopian Highlands (Williams and Funk 2011). How changes in temperature and rainfall will affect river flows and hence water availability for irrigation and hydropower is even less certain (Melesse *et al.* 2011).

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 development of hydraulic infrastructure on the main stem of the river and have, with one exception (Block and Strzepak 2010), assessed impacts in relation to current climate conditions. Relatively little consideration has been given to the impact of water diversions and development on the tributaries, and scant attention has been paid to the possible water resource implications of climate change. The lack of information on water resources and the implications of different investment options remain a major impediment to building consensus between the riparian states (Jägerskog *et al.* 2007).

This paper reports the findings of research conducted to determine the impact of one climate change scenario (A1B) on the performance of existing and planned irrigation and hydropower schemes in Ethiopia and the implications for flows into Sudan. For this work we have combined climate change, hydrological and water resource models. All simulations were conducted for a 128-year period (1983–2100). Although necessarily based on many assumptions, not least that something similar to the A1B scenario is the most likely to occur, the work illustrates how relatively simple models, used in combination, can provide useful information for possible future water resource development in the basin. However, in evaluating the implications for decision making it is clear that without a wide range of other inputs the modelling results alone are insufficient for detailed policy formulation.

Study area

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 1). It leaves the south-eastern 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 Precambrian 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 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 m asl from where it flows to Khartoum and joins the White Nile. The catchment area of the Blue Nile at the border is approximately 176,000 km².

Within the basin, rainfall varies significantly with altitude and is to a large extent controlled by the movement of air masses associated with the Intertropical Convergence Zone. There is considerable interannual variability, but rainfall increases from about 1000 mm/y near the border to between 1400 and 1800 mm/y over parts of the upper basin and exceeds 2000 mm/y in some places in the south (Awulachew *et al.* 2008). The summer months account for a large proportion of mean annual rainfall; averaged across the basin, approximately 70% occurs between June and September.

Potential evapotranspiration also varies considerably and, like rainfall, is highly correlated with altitude. In the highlands of Ethiopia, potential evapotranspiration ranges from

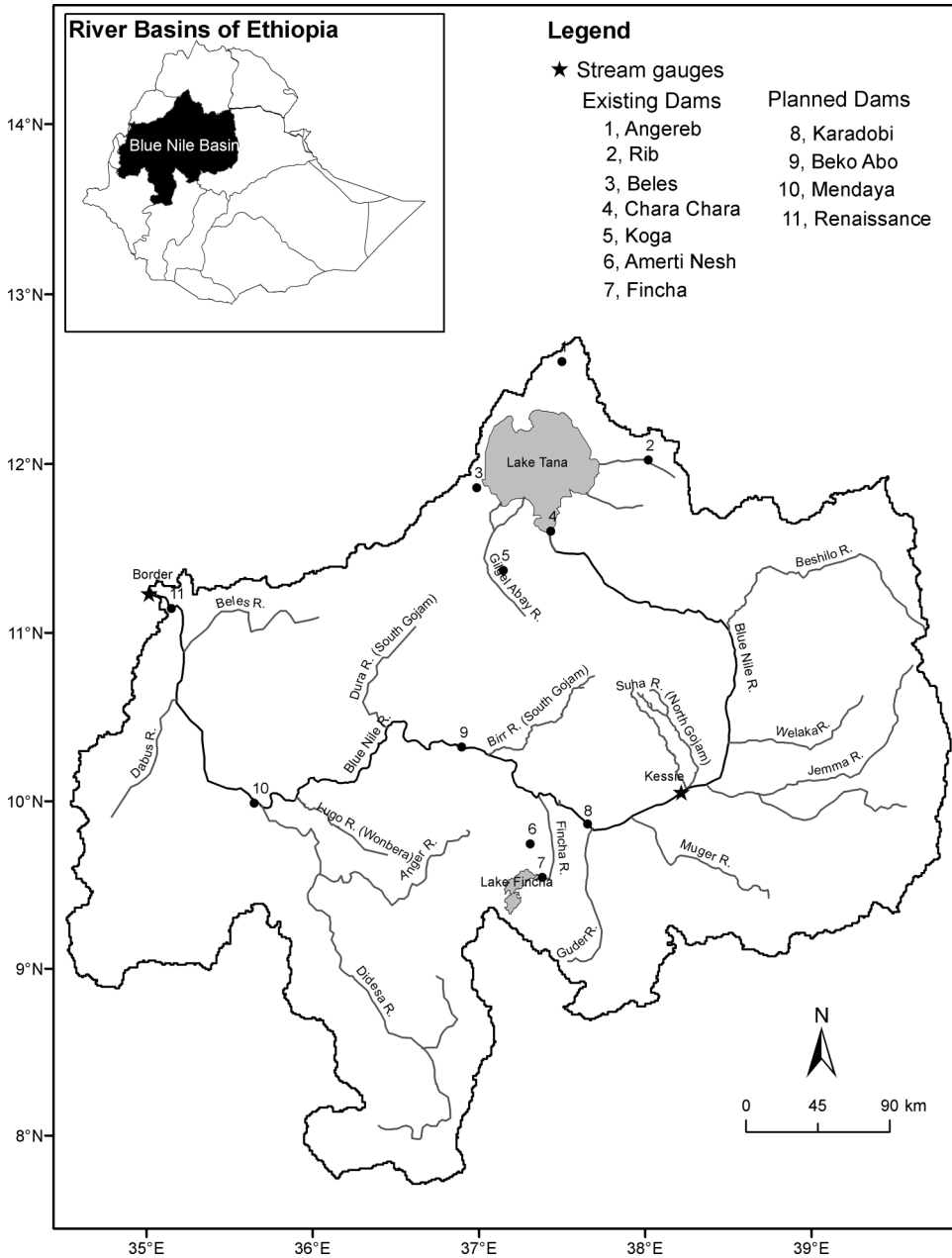


Figure 1. Map of the Blue Nile River and its sub-basins to the border with Sudan showing the major tributaries and the gauging stations at Lake Tana, Kessie and the border.

approximately 1300 to 1700 mm/y and in many places is less than rainfall in the rainy season. Consequently, rainfed cultivation, producing a single crop in the rainy season, is possible – though risky in low-rainfall years (Awulachew *et al.* 2008).

The flow of the Blue Nile is characterized by extreme seasonal and interannual variability. At Kessie and the Ethiopian-Sudan border (Figure 1) annual flow varies from approximately 180 m³/s to 1040 m³/s (i.e. 5.6 km³/y to 32.8 km³/y) and from 1,410 m³/s

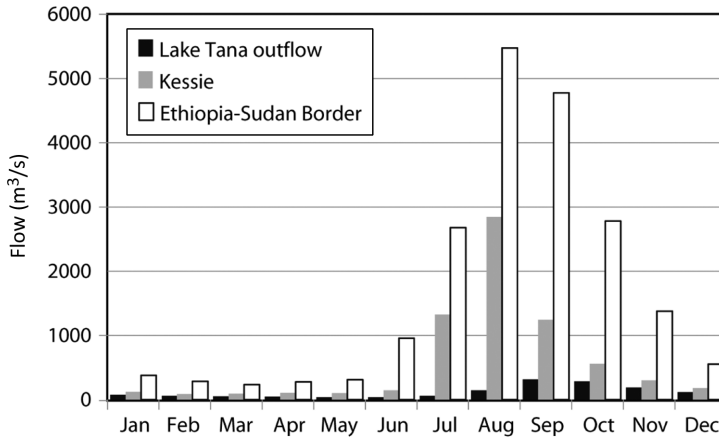


Figure 2. Mean monthly flow at gauging stations located on the main stem of the Blue Nile. (Data provided by the Hydrology Department of the Ministry of Water Resources, Ethiopia.)

to 1,964 m³/s (i.e. 44.5 km³/y to 61.9 km³/y) respectively. Mean monthly flow also varies considerably (Figure 2). Typically, more than 80% of the flow occurs during the wet season (July to October) while only 4% of the flow occurs during the dry season (February to May) (Awulachew *et al.* 2008). The high variability in both rainfall and flow mean that water storage is a critical component of water resources development in the basin.

Current water resource development

To date, Ethiopia has utilized very little of the Blue Nile water, partly because of its inaccessibility, partly because the major centres of population lie outside the basin and partly because there has been very limited development of hydraulic infrastructure on the river. Until recently only three, relatively minor, hydraulic structures have been constructed in the Ethiopian part of the catchment (Table 1). The Chara Chara weir and Finchaa Dam 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% of the total installed generating capacity of the country in 2009 (i.e. 1618 MW, of which 95% was hydropower) (EEPCo, 2010). In 2010, a new power station on the Beles River came on line, which utilizes water diverted into the Beles River from Lake Tana and has an installed capacity of 460 MW. By April 2011, the total installed capacity within the country had increased to 2060 MW, of which 29% was within the Blue Nile basin.

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 schemes in the Ethiopian part of the catchment are the Finchaa sugar-cane plantation (8145 ha), which utilizes water after it has passed through the Finchaa hydropower plant, and the Koga scheme (7200 ha), which uses water flowing into Lake Tana and was constructed in 2010 (Table 1).

Future water resource development

The Ethiopian government contends that utilization of the Nile water resources both for irrigation and hydropower is essential for socio-economic development and poverty

Table 1. Existing dams in the Ethiopian 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 84 MW) and since 2010 for transfer of water to the Beles River hydropower station (installed capacity 460 MW).
Finchaa*	Finchaa	2,395	1971	Regulation for hydropower production (installed capacity 134 MW) and also sugar cane irrigation (8145 ha)
Koga	Blue Nile	83.1	2010	Regulation of flow in the Koga River, a major tributary flowing into Lake Tana, for small-holder irrigation (7200 ha).

+ This is the active storage of Lake Tana that is controlled by the operation of the weir (i.e. lake levels between 1784 m asl and 1787 m asl). It represents 2.4 times the average annual outflow of the lake.

* A small dam located on the Amerty river (storage 40 Mm³) diverts water from the Amerty into the Finchaa reservoir.

alleviation. Current planning is focused primarily on the Lake Tana and 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 Consulting Engineers 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 (<200 ha), 130,395 ha of medium (200–3000 ha) and 639,330 ha of large (>3000 ha) 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 four largest schemes being considered are dams on the main stem of the Blue Nile River (i.e. Karadobi, Mendaya, Beko Abo and Border). Of these schemes, the furthest advanced was the Karadobi project, for which the pre-feasibility study was conducted in 2006 (Norconsult 2006). However, recently the government has announced that the Border Dam (now called the Renaissance Dam) is the one that will proceed first. The original planned generating capacity of the Border Dam was 1400 MW, but in the current plans this has been increased to 5250 MW (Davison 2011).

In addition to the single-purpose hydropower schemes, it is anticipated that electricity generation will be added to several of the proposed irrigation projects where dams are being built. It is estimated that this could provide an additional 216 MW of capacity (BCEOM 1998). Hence, the total generating capacity of all the hydropower schemes being considered in the Blue Nile may exceed 10,000 MW. Currently, it is anticipated that much of the electricity generated by these power stations will be sold to Sudan and possibly Egypt.

Method

In this study, three models were combined (Table 2). The IPCC SRES-AR4 A1B emissions scenario was used as the basis for the climate change analyses. This scenario describes a

Table 2. Models used to evaluate the implications of climate change on existing and future water resource development in the Blue Nile.

Climate modelling

COSMO-CLM (CCLM) is a dynamic, non-hydrostatic regional climate model (Davin *et al.* 2011). The data used for this study were taken from COSMO_4.0_CLM simulations, run for the African continent with grid spacing of 0.5°. The model has 32 vertical layers and 10 soil layers. The simulations comprised 30 years of daily control runs using ECHAM5-OM (1971–2000) and 100 years of transient scenario runs using ECHAM5, A1B climate scenarios (2001–2100). The initial and boundary conditions were taken from the ECMWF Re-analysis (ERA40) (Hattermann 2011). A bias correction was performed for the results from the CCLM simulated temperature and precipitation using CRU data (Mitchell and Jones 2005) as reference and comparing against the simulated data on a monthly time step for the 30-year reference period 1971–2000. For each grid cell the long-term observed data were compared to the simulated data and the average bias was computed to derive a vector of 12 correction factors (i.e. one a month) for each cell. The climate projections were corrected by this bias for each simulation day and at each grid cell using the monthly correction factors (Hatterman 2011).

Hydrological modelling

The Soil and Water Assessment Tool (SWAT) is a rainfall-runoff model (Arnold *et al.* 1998). It operates on a daily time step on sub-basins identified using a digital elevation model. Similar land-use, soil characteristics and topography (slope) within each sub-basin are lumped together into hydrological response units (HRUs). In this study, 18 sub-basins and 185 HRUs were identified. The model was first set up using observed daily climate data for the period 1961–1990 derived from eight meteorological stations located within the basin. Each station was assigned to a sub-basin based on proximity. Due to missing data and short records, only daily precipitation and temperature time series were used as input for SWAT; other required parameters (e.g. solar radiation and humidity) were generated using a weather generator. Historic flow records at two stations (i.e. at Kessie and at the Ethiopia-Sudan border) were used to calibrate and validate the model. For the future climate change scenario, data were extracted by superimposing the locations of the eight stations used to simulate historical runoff over the grid of the CCLM model (Girma 2011). Output from the model comprised potential and actual evapotranspiration as well as flow and groundwater recharge for each sub-basin. The SWAT model was calibrated and validated using measured dekad^a stream flow data collected at El Diem at the Ethiopia-Sudan border. The total available historical discharge data (1961–1990) was divided into two sets: 20 years for calibration (1961–1980) and 10 years for validation (1981–1990). Parameters which are relatively important in determining runoff in tropical regions were modified first manually and then using an automatic calibration procedure (Girma 2011).

Water resource modelling

The Water Evaluation and Planning (WEAP) model is used to evaluate planning and management issues associated with water resource development (Yates *et al.* 2005, SEI 2007). It calculates a mass balance of flow sequentially down a river system, making allowance for human-induced abstractions and inflows. It is typically used to simulate alternative scenarios comprising 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. 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, as identified by the Ministry of Water Resources and Energy. It was used with flows generated by the SWAT model for the period 1983–2100 to evaluate the impact of the A1B climate change scenario on the performance of the water resource schemes. The SWAT flow was generated within 18 sub-basins; a simple method of area-weighting was used to convert these to the 16 WEAP sub-basins. Rainfall and evapotranspiration data, required for irrigation schemes and reservoirs, were also taken from the SWAT model output, and varied depending on in which sub-basin they were located. The WEAP model was calibrated and validated by simulating the recent past (i.e. 1983–2005) and comparing simulated and observed flows at both Kessie and the border as well as simulated and observed levels in Lake Tana. The results effectively showed the combined effect of all the model simulations and indicated that the simulated flow hydrographs were reasonable and that in relation to mean monthly flows the models performed well.

Note: ^aA dekad is a unit of time in a month. The first 10 days of the month constitute the first dekad, the second 10 days constitute the second dekad and the remaining days (8 to 11) constitute the third dekad.

future world of very rapid economic growth, global population that peaks at 8.7 billion in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. It is distinguished from other scenarios by the technological emphasis on a balance between fossil-intensive and non-fossil energy sources (IPCC 2000). This scenario was selected simply because it is a midrange scenario resulting in climate changes that lie between those anticipated by other scenarios.

A dynamic regional climate model – COSMO-CLM (CCLM) – was used to determine climate projections for the basin for the period 1983–2100 with initial and boundary conditions set by the ECHAM-5 model (Hatterman 2011). The outputs generated from CCLM (i.e. rainfall, temperature and potential evapotranspiration) were used as inputs to a hydrological model (SWAT) which was set up, calibrated and validated with observed climate and hydrological data. Land use was assumed constant throughout the scenario simulation. Results of the SWAT modelling (i.e. projections in river flow and groundwater recharge), in conjunction with projected water demand, were used as inputs to the Water Evaluation and Planning (WEAP) model.

To evaluate the combined impact of water resources development and climate change, four scenarios were created: one without any human interventions and three with different levels of development (Table 3). Each scenario was simulated in WEAP over the full period of the climate change scenario (i.e. 1983–2100). 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. Details of the planned and future schemes were derived from pre-feasibility, feasibility and technical reports, where these exist, as well as from the basin master plan (e.g. Lahmeyer Consulting Engineers 1962, USBR 1964, WAPCOS 1990, BCEOM 1998, Beyene and Abebe 2006, Norconsult 2006, ENTRO 2007a; ENTRO 2007b). It was necessary to make several assumptions, particularly about irrigation demands and the return flows from irrigation schemes. Summary statistics of the three scenarios are presented in Table 4.

Table 3. Water resource development scenarios.

Scenario	Description
Natural	No water resource development. The “natural” system without any hydropower or irrigation schemes included.
Current development	The present water resource development (i.e. irrigation and hydropower schemes) with the exception of the Tana Beles transfer, which has only just come online.
Intermediate development	Planned water resource development – including the Tana Beles transfer – that is anticipated to occur in the near- to medium-term future (i.e. before approximately 2025). This includes all schemes for which feasibility studies have been conducted. Because the plans have only just been announced, the Karadobi Dam is included in this scenario but the Border (or Millenium) Dam is not.
Full development	All planned water resource development that is likely to occur in the future (before 2050). In addition to those schemes that were included in the intermediate-development scenario this includes all schemes identified in the basin master plan, including all the mega-dams on the main stem of the river.

Table 4. Comparison of reservoir storage, irrigated area and installed hydropower generating capacity for the four “development” scenarios.

Scenario	Total reservoir storage (km ³)	Irrigated Area (ha)	Installed hydroelectricity generating capacity (MW)
Natural	0 [†]	0	0
Current development	11.6 ⁺	15,345	218
Intermediate development	70.2 ⁺	272,018	2,194
Full development	167.1 ⁺	364,355	10,276*

[†] Includes the natural Lake Tana, but no human-made regulation of flows.

⁺ Includes regulated storage in Lake Tana (9.1 km³).

*Past estimates of potential installed capacity were 6426 MW. However, this has increased significantly with the plan for 5250 MW at the Millennium Dam alone.

To isolate the impacts of climate change, each development scenario was simulated in conjunction with the climate change scenario. For each month of simulation, net evaporation from Lake Tana and the reservoirs was estimated from the rainfall and potential evaporation data generated by the CCLM model and averaged over sub-basins in the SWAT model. Similarly for each month of simulation, irrigation demand (m³/ha) in each sub-basin was estimated from an empirical relationship that linked irrigation demand, estimated in the Ethiopia Basin master plan, to net rainfall (i.e. rainfall–potential evapotranspiration). This enabled estimates of modified future irrigation demand, arising from changed rainfall and temperature (as predicted in CCLM), to be computed. However, no allowance was made for changes in crops or agricultural practices.

To facilitate comparison between the four scenarios, results were summarized over three periods: 1983–2012, 2021–2050 and 2071–2100. Basin average results were computed from sub-basin results using a method of area weighting.

Results

Climate and hydrology

Figure 3 and Table 5 summarize changes in key climatic and hydrological variables (basin average temperature, rainfall, potential evapotranspiration and flow at the Ethiopia-Sudan border) over the period 1983 to 2100 as derived from the CCLM and SWAT models. There is some spatial variability, but it is beyond the scope of this paper to discuss this. The models predict that for the A1B scenario, averaged across the basin, there will be: 1) an increase in temperature; 2) a decline in rainfall; 3) an increase in potential evapotranspiration; and 4) a decrease in flow at the border. However, it is predominantly in the second half of the century that significant changes in these variables occur. In fact, despite a slight decline in mean annual rainfall, the flow at the border increases slightly (by approximately 5%) in the period 2021–2050.

Irrigation

As a consequence of the changes in rainfall and potential evapotranspiration, average irrigation demand (per ha) shows an increasing trend across the basin (Figure 4). Table 6 summarizes the increased demand (arising because of both the increased demand per ha and because of the increased irrigated area) as well as the unmet demand in each of the three scenarios.

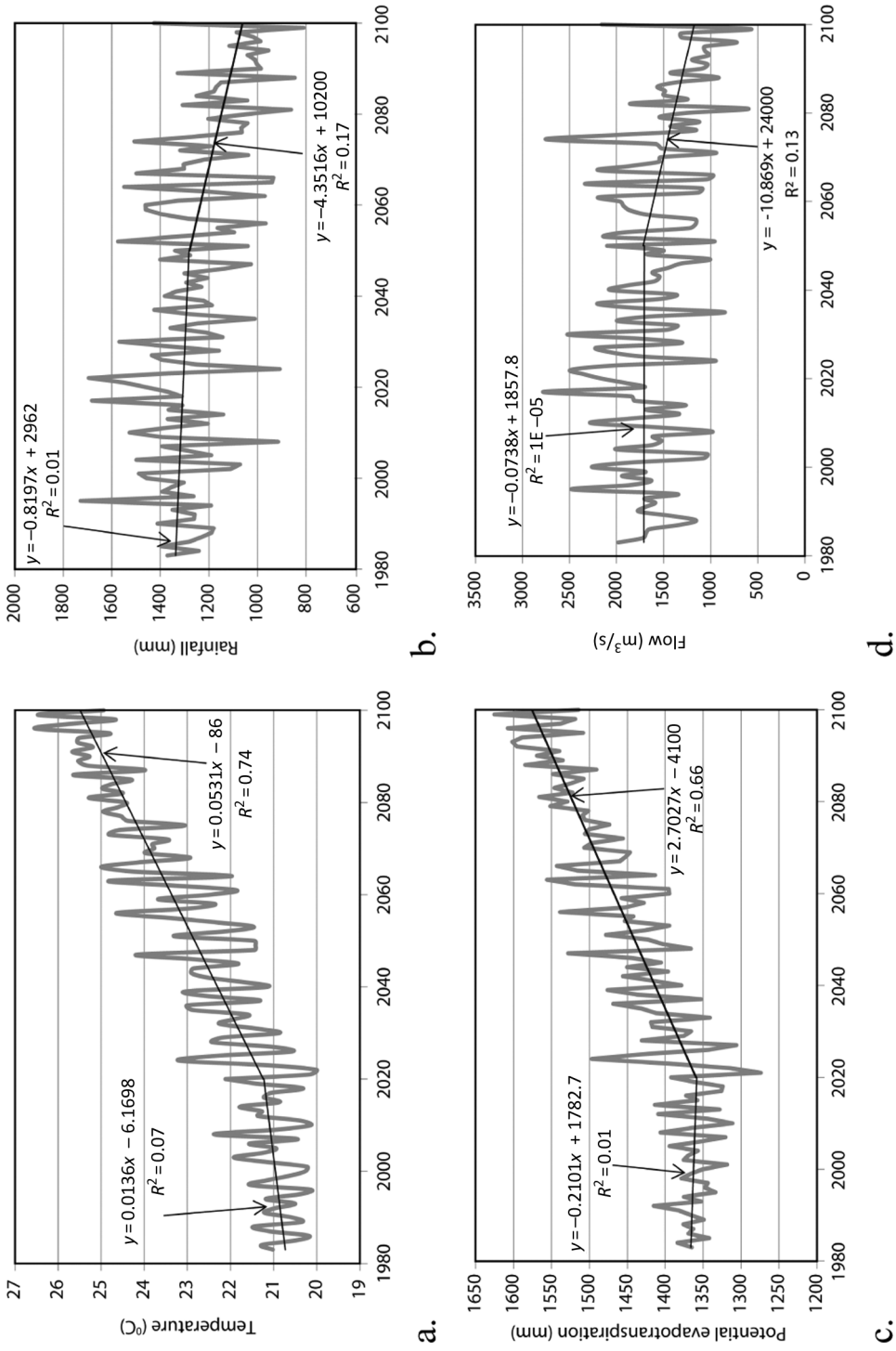


Figure 3. Basin average annual climate variables, 1983–2100: a. temperature; b. rainfall; c. potential evapotranspiration; d. flow at the Ethiopia-Sudan border.

Table 5. Basin averaged climatic and hydrological variables for the three periods 1983–2012, 2021–2050 and 2071–2100.

	Average annual temperature (°C)	Rainfall (mm)	Potential evapo-transpiration (mm)	Actual evapo-transpiration (mm)	Averaged annual flow at the Ethiopia-Sudan border (m ³ /s)
1983–2012	20.9	1310	1,363	539	1661
2021–2050	21.9	1290	1,405	522	1720
2071–2100	24.9	1110	1,535	525	1336

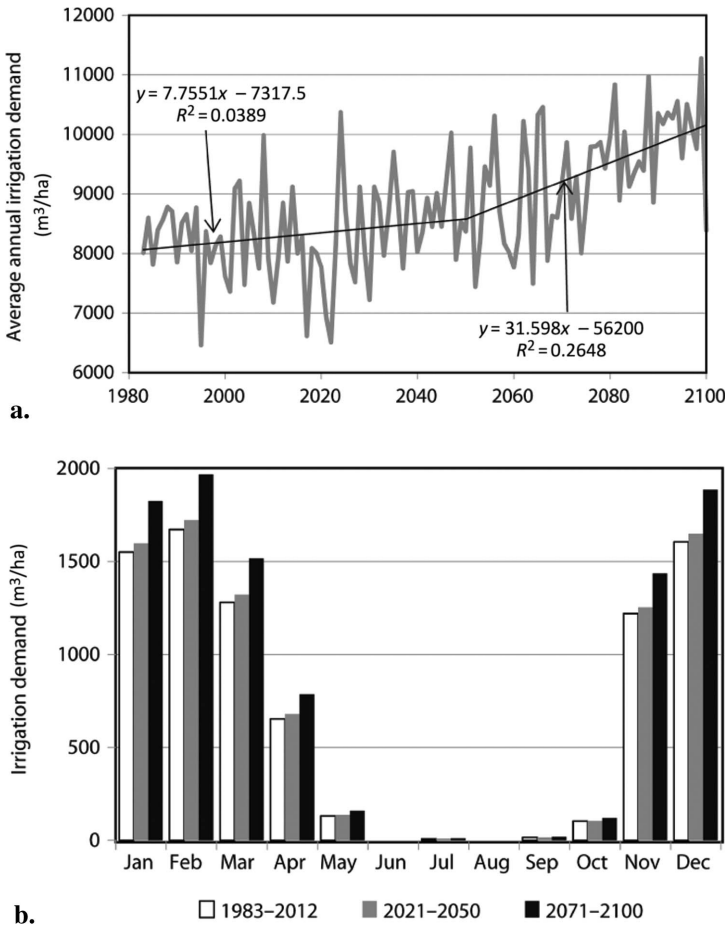


Figure 4. Predicted catchment average irrigation demand: a. annual values (1983–2100); b. mean monthly values over three periods: 1983–2012, 2021– 2050, and 2071–2100.

Hydropower generation

Figure 5 shows the simulated hydroelectricity generated each year in each scenario and Table 7 presents the average for each scenario over the three periods 1983–2012, 2021–2050 and 2071–2100. These results show a very significant increase in hydroelectricity produced as a consequence of the increased generating capacity between

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Table 6. Changes in total irrigation demand and unmet demand and in each of the three development scenarios.

	Catchment average irrigation demand (m ³ /ha)	Current development			Intermediate development			Full development		
		Water demand ¹ (km ³)	Unmet demand (km ³)	Demand delivered (%)	Water demand ¹ (km ³)	Unmet demand (km ³)	Demand delivered (%)	Water demand ¹ (km ³)	Unmet demand (km ³)	Demand delivered (%)
1983–2012	8,244	0.128	0	100	2.012	0.227	89	2.787	0.363	87
2021–2050	8,491	0.133	0.002	99	2.214	0.265	88	2.928	0.265	91
2071–2100	9,726	0.153	0.055	64	2.618	1.709	36	3.394	2.076	40

¹ Total water demand in each scenario was calculated based on the specific locations and the command area of the irrigation schemes functioning in that scenario.

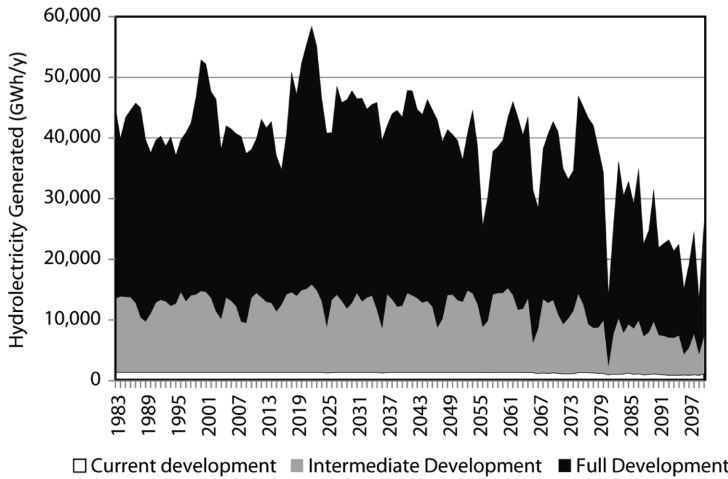


Figure 5. Simulated hydroelectricity generated each year (1983–2100) in each scenario.

Table 7. Changes in hydroelectricity generated and percentage of the total potential in each of the three development scenarios.

	Current development		Intermediate development		Full development	
	Hydroelectricity generated (GWh/y)	% of total potential	Hydroelectricity generated (GWh/y)	% of total potential	Hydroelectricity generated (GWh/y)	% of total potential
1983–2012	1397	100	12,814	98	40,803	91
2021–2050	1390	100	12,962	99	44,245	98
2071–2100	1138	82	8,422	64	28,449	63

current and full development. They also show that reduced river flows, arising as a consequence of climate change, will significantly reduce the amount of power generated in comparison to the potential (the total possible with the installed generating capacity, if flows did not change) – in the second half of the century.

River flow

The impact of both development and climate change on Lake Tana water levels and flows at key locations in the basin is presented in Figure 6 and summarized in Table 8. These results indicate:

- (1) a decline in the outflow from Lake Tana but slight increases in flow at both Kessie and the border over the first half of the century
- (2) significant declines in flow at all locations in the second half of next century.

The outflow from Lake Tana is reduced more significantly than at the other locations because of the diversion of water to the Beles catchment. This change is also reflected in the lake water levels, with average annual levels dropping below the minimum level required for shipping on the lake (1784.5 m asl) at the end of the century in all three

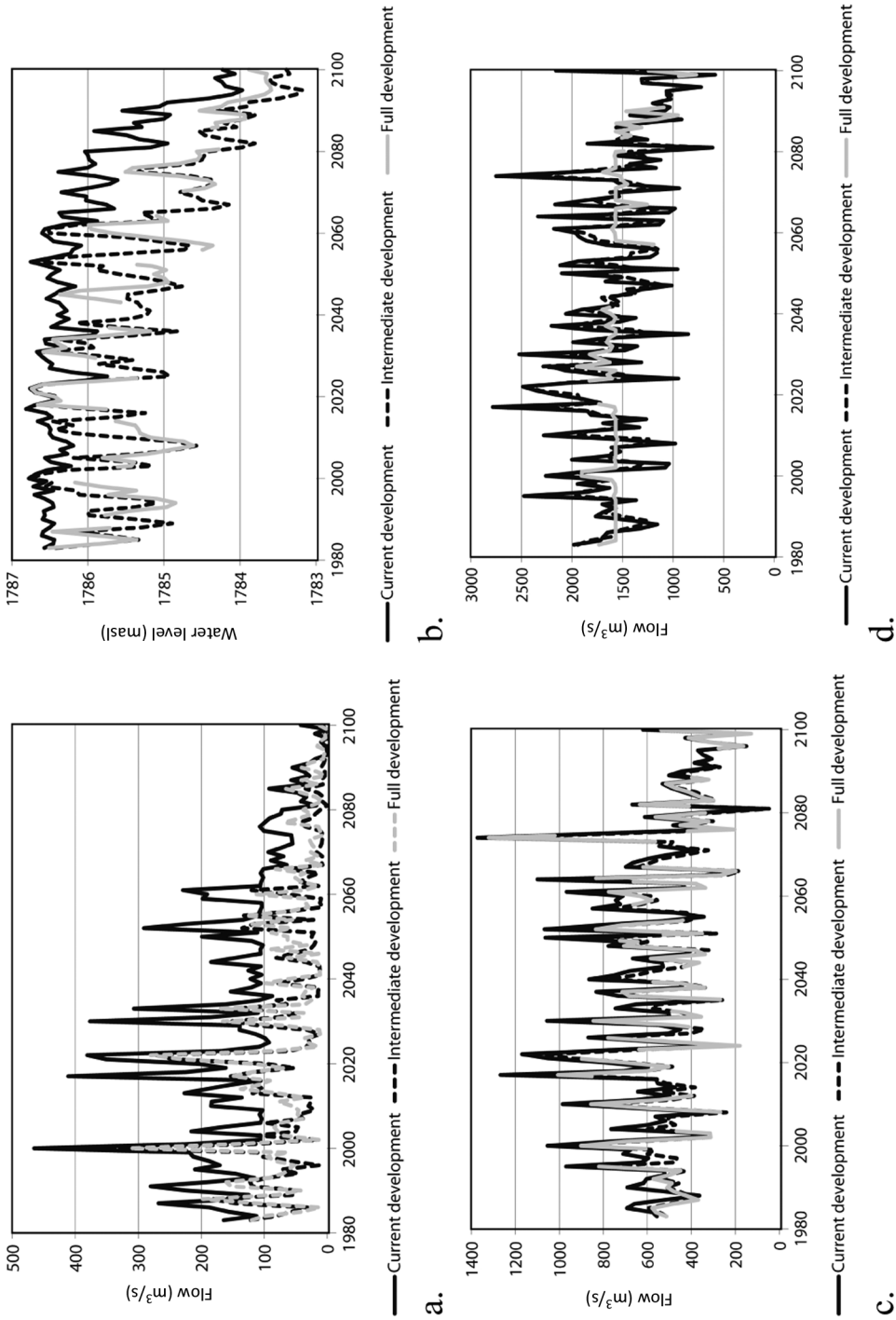


Figure 6. For each of the three development scenarios, simulated changes (1983–2100) in: a. outflow from Lake Tana; b. water levels in Lake Tana; c. flow at Kessie; d. flow at the Ethiopian-Sudan border.

Table 8. Changes in river flow (m^3/s) at three locations in the basin in the natural scenario and each of the three development scenarios.

	Natural			Current development			Intermediate development			Full development		
	Outflow Tana	Kessie	Border	Outflow Tana	Kessie	Border	Outflow Tana	Kessie	Border	Outflow Tana	Kessie	Border
1983–2012	180	620	1661	177	617	1655	81	522	1622	87	528	1599
2021–2050	160	661	1720	158	659	1713	61	563	1678	63	564	1683
2071–2100	46	446	1336	45	444	1327	10	409	1305	21	421	1301

development scenarios (Figure 6b). However, it is interesting that the lowest levels and outflow from Lake Tana occur in the Intermediate Development scenario and there is a slight improvement in the Full Development scenario. This suggests that increased water storage in the catchment relieves some of the pressure on the Lake and results in a small improvement.

Comparison of the flow at the border between the three development scenarios also indicates the impact of increased flow regulation. In the Full Development scenario flows are significantly less variable than in the other two scenarios, and in the latter part of the century the periods of lowest flow are reduced slightly as a consequence of upstream storage (Figure 6d).

Discussion

The Ethiopian government's policy is to significantly increase large reservoir water storage in the Blue Nile basin in order to support national development. The planned increases in water storage will facilitate significant increases in hydropower generation and irrigation in the basin. If all planned development occurs, large-reservoir water storage will exceed 160 km^3 (approximately 14 times present levels and 3 times the current mean annual flow at the Ethiopia-Sudan border), irrigation will exceed 360,000 ha (23 times current levels) and installed hydropower generating capacity will be in excess of 10,000 MW (47 times current levels).

Results from this study indicate that changes in climate will affect the basin hydrology. Under a midrange climate change scenario (A1B), in a natural situation (i.e. no development), flows increase at both Kessie and the border in the first half of the twenty-first century. This is despite slightly reduced rainfall and increased potential evapotranspiration and highlights the fact that it is not only the absolute values but also the temporal distribution of climate variables (particularly rainfall) that influence the basin runoff regime. However, even in a no-development scenario, average annual flows decrease significantly at all locations in the second half of the century: by approximately 74% from Lake Tana, 28% at Kessie and 20% at the border. The very large decrease in outflow from Lake Tana is a consequence of the fact that in the second half of the century water levels in the lake drop below 1784 m asl – the crest of the rock outcrop at the outlet, and also the minimum level at which flows can be released by the Chara Chara weir – for increasingly long periods of time.

The planned water resources development in the basin will cause additional reductions in flows. However, with the exception of Lake Tana, where the diversion to the Beles results in a very significant decrease in levels and outflow, the additional decline in flows is relatively modest. For example, under the full development scenario, the development of

irrigation and hydropower results in an additional 8.3% decline in the flow at Kessie and an additional 2.6% decline in the flow at the border in the second half of the century.

The changes in climate predicted for the A1B scenario will have significant impacts on both hydropower generation and irrigation. The model simulations indicate that approximately 90% of irrigation demand will be met and the hydropower generated will broadly match the potential until the middle of the twenty-first century. However, in the latter part of the century, in the Intermediate and Full Development scenarios, 40% or less of the total irrigation demand will be met and only approximately 60% of potential hydropower will be generated (Figure 7). It is clear that increased water storage in large reservoirs increases the area of land that can be irrigated and the amount of electricity that can be generated. However, it is also clear that, if an A1B type scenario comes to pass, the performance of that development will be curtailed as a consequence of climate change.

These results indicate the possible implications of one climate scenario in combination with different levels of water resource development. They illustrate how modelling can be used to determine possible implications of climate change and provide a useful contribution to the debate about how the water resources of the Blue Nile in Ethiopia might be best utilized in the future. However, even ignoring the large degree of unquantifiable uncertainty associated with them, the results paint a complex picture in which there is no straightforward answer to the key question of whether investment in large-scale infrastructure should proceed. There is no win-win solution. 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 short-to-medium term with only marginal impacts on flow downstream in Sudan. This economic development, if utilized wisely, could help alleviate poverty and contribute to increased community resilience to adverse climate impacts. However, by the end of the twenty-first century the effectiveness of the infrastructure is likely to be significantly undermined by climate change, thereby constraining further contributions to the national economy and possibly adversely affecting many peoples' well-being and livelihoods. Furthermore, impacts on downstream flow in Sudan would, as a consequence of climate change and water resource development in Ethiopia, be much greater.

Conclusion

Although there remains great uncertainty about how climate change will impact the water resources of the basin, it is clear that even with massively increased water storage, under a midrange scenario, the performance of planned irrigation and hydropower schemes is likely to be severely constrained by the end of the twenty-first century. Harsher climate change – which, based on current emissions trends, is perhaps more likely – would presumably have even more severe effects. Hence, adaptation to climate change, effective water resources management, and development are clearly linked and need to be considered together.

As highlighted in this study, modelling has an important role to play in evaluating the possible impacts of different development options and scenarios. However, policy formulation is a complex process that should never be based solely on model results. Although the modelling conducted in this study is a useful contribution to greater understanding of what may happen in the basin as a consequence of climate change, the results do not enable policy formulation on their own. The modelling has provided quantitative information for evidence-based decision making, but this is not sufficient to formulate detailed policy recommendations. A wide range of other information, as well as inputs from a large number

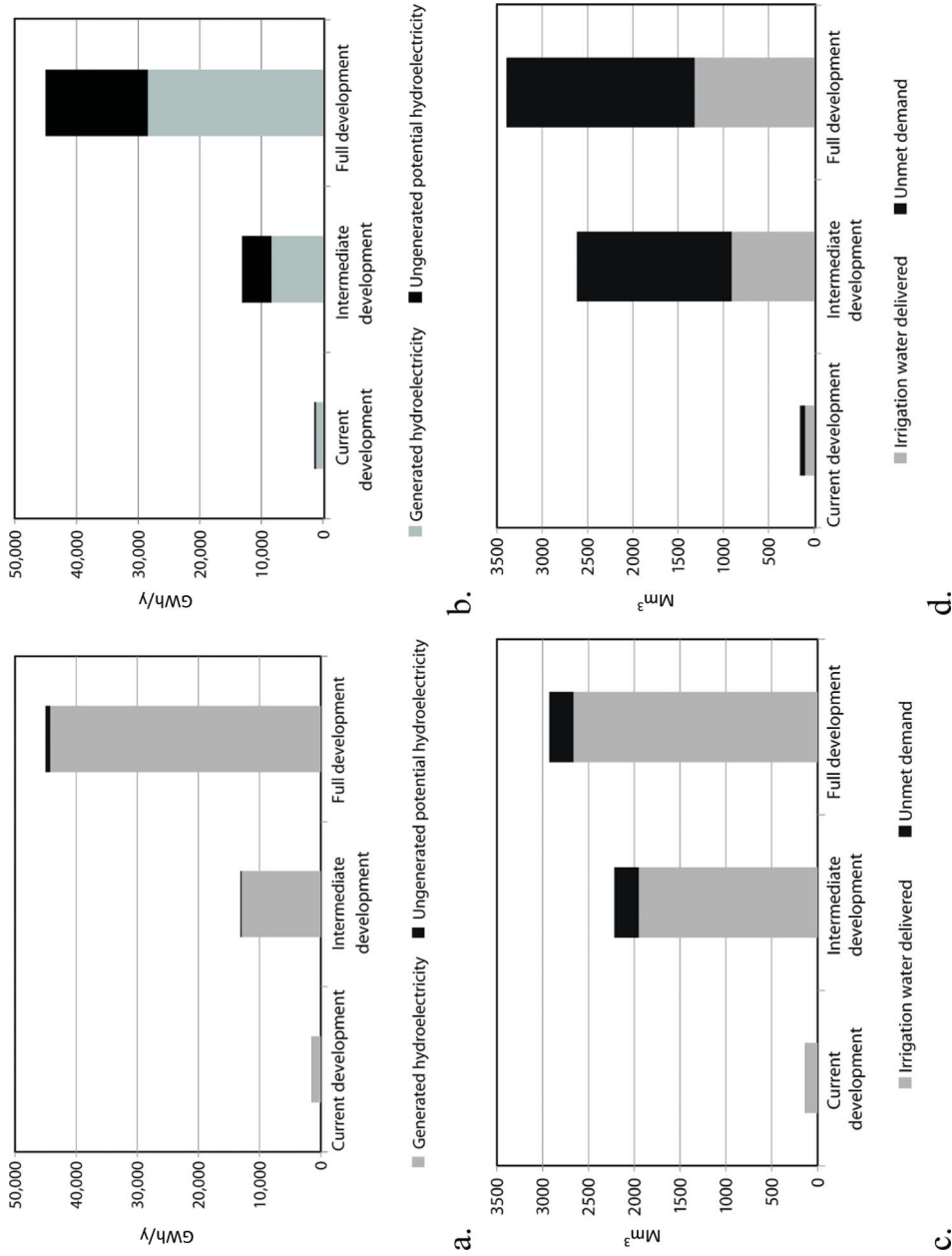


Figure 7. Comparison of simulated water resources development: - hydroelectricity generated: a. 2021–2050, and b. 2071–2100; and irrigation demand; c. 2021–2050, and d. 2071–2100.

of diverse stakeholders – including, in this case, downstream stakeholders in Sudan and Egypt – needs to be incorporated in the process.

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