Implications of climate change on existing and planned Water Resource Development in the Upper Blue Nile

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Introduction
There are plans for significant expansion of hydropower and irrigation in the Ethiopian portion of the Blue Nile River Basin. However, the possible consequences of climate change on the performance of existing and planned schemes have not previously been evaluated. In this study, a mid-range climate change scenario (A1B) was evaluated in tandem with four development scenarios, each reflecting different levels of water resource development in the basin. The period 1983 to 2100 was simulated. The results indicate: i) a moderate increase in temperature but a slight decline in potential evapotranspiration to 2020, followed by a rapid increase in both thereafter; and ii) very little change in rainfall and flow at the Ethiopia-Sudan border till 2050, followed by a rapid decline in both thereafter. These changes will affect the technical performance of reservoirs and hence irrigation and hydropower schemes. By the end of the 21st century the model simulations of the A1B scenario in conjunction with the full development scenario, anticipate: i) average basin-wide irrigation demand will increase from 8,244 m$^3$ ha$^{-1}$ to 9,726 m$^3$ ha$^{-1}$; ii) average annual unmet irrigation demand will be 2,076 Mm$^3$ and iii) annual hydropower generation will equate to just 63% of the potential that could be generated (i.e. 28,449 out of 45,000 GWh$^{-1}$). Furthermore, flow at the Ethiopia-Sudan border will be reduced by approximately 23% (i.e. from 1,661 m$^3$ s$^{-1}$ to 1,301 m$^3$ s$^{-1}$).

1. Background
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 basins water resources cooperatively are currently limited and tensions remain (Metawie, 2004). Despite the potential benefits of regional cooperation and integrated joint basin management, all three countries continue to pursue unilateral plans for development (Whittington et al., 2005; Cascão, 2009).

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 on increased precipitation in eastern Africa (Christensen et al., 2007). The IPCC AR4 therefore states that increased precipitation is “likely”. However, a more recent study has indicated a decrease in convection and hence reduced rainfall over much of the eastern flank of Ethiopian Highlands (Williams and Funk, 2010). 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 Strzepek, 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).

2. Study Area
The Blue Nile River (known as the Abay River in Ethiopia) rises in the Ethiopian highlands and initially flows northward into Lake Tana, which is located at an elevation of just under 1,800 m (Fig. 1). It leaves the southeastern corner of the Lake, flowing first south-east, before looping back on itself, flowing west and then turning north-west close to the border with Sudan. In the highlands, the catchment is cut by deep ravines in which the major tributaries flow and there are many suitable locations for dams. The Blue Nile enters Sudan at an altitude of 490 masl 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.

![Map of the Blue Nile to the border with Sudan showing some existing and planned dams as well as the flow gauging station at the Ethiopia-Sudan border](image)

Fig. 1. Map of the Blue Nile to the border with Sudan showing some existing and planned dams as well as the flow gauging station at the Ethiopia-Sudan border

Within the basin, rainfall varies significantly with altitude. There is considerable inter-annual variability, but it increases from about 1,000 mm near the border to between 1,400 and 1,800 mm over parts of the upper basin and exceeds 2,000 mm in some places in the south. Approximately 70% of annual rainfall occurs between June
and September. Potential evapotranspiration also varies considerably and, like rainfall, is highly correlated with altitude ranging from approximately 1,300 to 1,700 mm y⁻¹ (Awulachew et al., 2008).

The flow of the Blue Nile is characterized by extreme seasonal and inter-annual variability. At the Ethiopian-Sudan border annual flow varies from approximately 1,410 m³ s⁻¹ to 1,964 m³ s⁻¹ (44.5 Bm³ to 61.9 Bm³). 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 critically important for water resource development in the basin.

To date, Ethiopia has utilized very little of the Blue Nile water. Until recently only three relatively minor hydraulic structures have been constructed. The Chara Chara weir and Finchaa dam were built primarily to provide hydropower. They regulate flow from Lake Tana and the Finchaa River respectively. In 2010, a new power station on the Beles River, which utilizes water diverted from Lake Tana started operating. Within the Blue Nile basin the usable installed capacity is currently 597 MW, 29% of the country’s current total of 2,060 MW. Agriculture, the main occupation of the inhabitants in the basin, is primarily rain-fed with almost no irrigation. Currently, the only formal irrigation schemes are the Finchaa sugar cane plantation (8,145 ha), which utilizes water after it has passed through the Finchaa hydropower plant and the Koga scheme (7,200 ha), which uses water flowing into Lake Tana and was constructed in 2010. In contrast there is over 1 million ha of irrigation downstream in Sudan.

The Ethiopian government contends that utilization of the Nile water resources both for irrigation and hydropower is essential for socio-economic development and poverty alleviation. 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 and the total potential irrigated area is estimated to be 815,581 ha of which plans exist to develop 364,355 ha (BCEOM, 1998). In addition, more than 120 potential hydropower sites have been identified (WAPCOS, 1990; Beyene and Abebe, 2006). Of these, 26 were investigated in detail during the preparation of the Abay River Basin Master Plan (BCEOM, 1998). The four largest schemes are dams on the main stem of the Blue Nile River (i.e. Karadobi, Mendaya, Beko Abo and Border). Recently the government announced that the Border Dam (now called the Renaissance Dam) is the one that will proceed first and work has commenced on the construction of this scheme with a planned installed capacity of 5,250 MW. The total generating capacity of all the hydropower schemes being considered in the Blue Nile may exceed 10,000 MW. 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. A dynamic regional climate model, COSMO-CLM (CCLM) (Davin et al. 2011), was used to determine climate projections for the basin for the period 1983-2100 (Hattermann, 2011). The outputs generated from CCLM (i.e., rainfall, temperature and potential evapotranspiration) were used as input to a hydrological model (SWAT) (Arnold et al., 1998) which was setup, calibrated and validated with observed climate and hydrological data (Girma, 2011). The outputs from the SWAT model (i.e., projections in river flow and groundwater recharge) were used as input to a water resources model (WEAP) (SEI, 2007, Yates et al., 2005) which was used to determine the water resources implications of the changes in climate.

The IPCC SRES-A1B emissions scenario was used as the basis for the climate projections. This scenario describes a 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). The scenario was selected because provides a broadly middle impact scenario with changes that, at the global level, lie between extremes produced by other emission scenarios (i.e., A2 - extensive fossil fuel use, and B2 - moderate increase in greenhouse gas concentrations).

To evaluate the combined impact of water resources development and climate change four development scenarios were considered: one without any human interventions and three with different levels of development (Table 1). Each scenario was simulated in WEAP. 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. 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 2.

Table 1. Water resource development scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>No water resource development. The “natural” system without any hydropower or irrigation schemes included.</td>
</tr>
<tr>
<td>Current development</td>
<td>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.</td>
</tr>
<tr>
<td>Intermediate development</td>
<td>Planned water resource development – including the Tana Beles transfer - that it is anticipated may 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 (aka Millenium) dam is not.</td>
</tr>
<tr>
<td>Full development</td>
<td>All planned water resource development that is likely to occur in the future (i.e. possibly 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.</td>
</tr>
</tbody>
</table>

Table 2. Comparison of reservoir storage, irrigated area and installed hydropower generating capacity for four “development” scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total reservoir storage (Mm³)</th>
<th>Irrigated Area (ha)</th>
<th>Installed hydroelectricity generating capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>0†</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Current development</td>
<td>11,578†</td>
<td>15,345</td>
<td>218</td>
</tr>
<tr>
<td>Intermediate development</td>
<td>70,244†</td>
<td>272,018</td>
<td>2,194</td>
</tr>
<tr>
<td>Full development</td>
<td>167,079†</td>
<td>364,355</td>
<td>10,276*</td>
</tr>
</tbody>
</table>

†Includes the natural Lake Tana, but no human-made regulation of flows
*Includes regulated storage in Lake Tana (9,100 Mm³)

Past estimates of potential installed capacity were 6,426 MW. However, this has increased significantly with the plan for 5,250 MW at the Millennium scheme alone.

3. Results

3.1 Climate and Hydrology

Table 3 summarize changes in key climatic and hydrological variables over the period 1983 to 2100 as derived from the CCLM and SWAT models. Although there is some spatial variability, the models predict that for the A1B scenario, averaged across the basin, there will be: i) an increase in temperature; ii) a decline in rainfall (Fig. 2a); iii) an increase in potential evapotranspiration and iv) a decrease in flow at the border (Fig. 2b).

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.

Table 3. Climatic and hydrological variables for three periods 1983-2012, 2021-2050 and 2071-2100

<table>
<thead>
<tr>
<th></th>
<th>Average annual temperature (°C)</th>
<th>Rainfall (mm)</th>
<th>Potential Evapotranspiration (mm)</th>
<th>Actual Evapotranspiration (mm)</th>
<th>Averaged annual flow at the Ethiopia-Sudan border (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983-2012</td>
<td>20.9</td>
<td>1,310</td>
<td>1,363</td>
<td>539</td>
<td>1,661</td>
</tr>
<tr>
<td>2021-2050</td>
<td>21.9</td>
<td>1,290</td>
<td>1,405</td>
<td>522</td>
<td>1,720</td>
</tr>
<tr>
<td>2071-2100</td>
<td>24.9</td>
<td>1,110</td>
<td>1,535</td>
<td>525</td>
<td>1,336</td>
</tr>
</tbody>
</table>
3.2 Irrigation
As a consequence of the changes in rainfall and potential evapotranspiration, average irrigation demand (per ha) shows an increasing trend across the basin. Table 4 summarizes the increased demand (i.e. arising because of both the increased per ha demand and because of the increased area irrigated) as well as the unmet demand in each of the three scenarios.

Table 4. Changes in total irrigation demand and unmet demand and in each of the three development scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Current Development Water Demand</th>
<th>Unmet Demand</th>
<th>Intermediate Development Water Demand</th>
<th>Unmet Demand</th>
<th>Full Development Water Demand</th>
<th>Unmet Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983-2012</td>
<td>8,244</td>
<td>128</td>
<td>0</td>
<td>2,012</td>
<td>227</td>
<td>2,787</td>
</tr>
<tr>
<td>2021-2050</td>
<td>8,491</td>
<td>133</td>
<td>2</td>
<td>2,214</td>
<td>265</td>
<td>2,928</td>
</tr>
<tr>
<td>2071-2100</td>
<td>9,726</td>
<td>153</td>
<td>55</td>
<td>2,618</td>
<td>1,709</td>
<td>3,394</td>
</tr>
</tbody>
</table>

Note: 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.

3.3 Hydropower generation
Table 5 presents the average hydroelectricity generated for each scenario. These results show a very significant increase in hydroelectricity produced as a consequence of the increased generating capacity between 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 in the second half of the century.

Table 5. Changes in hydroelectricity generated and percentage of the total potential in each of the three development scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Current Development Hydroelectricity generated (GWh⁻¹)</th>
<th>% of total potential</th>
<th>Intermediate Development Hydroelectricity generated (GWh⁻¹)</th>
<th>% of total potential</th>
<th>Full Development Hydroelectricity generated (GWh⁻¹)</th>
<th>% of total potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983-2012</td>
<td>1,397</td>
<td>100</td>
<td>12,814</td>
<td>98</td>
<td>40,803</td>
<td>91</td>
</tr>
<tr>
<td>2021-2050</td>
<td>1,390</td>
<td>100</td>
<td>12,962</td>
<td>99</td>
<td>44,245</td>
<td>98</td>
</tr>
<tr>
<td>2071-2100</td>
<td>1,138</td>
<td>82</td>
<td>8,422</td>
<td>64</td>
<td>28,449</td>
<td>63</td>
</tr>
</tbody>
</table>

3.4 River flow
The impact of both development and climate change on flows at the Ethiopia Sudan border are summarized in Table 6 indicating a slight increase in the first half of the century but a significant decrease in the second half.

Table 6. River flow (m³s⁻¹) at the Ethiopia-Sudan border in each of the four scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural</th>
<th>Current Development</th>
<th>Intermediate Development</th>
<th>Full Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983-2012</td>
<td>1,661</td>
<td>1,655</td>
<td>1,622</td>
<td>1,599</td>
</tr>
<tr>
<td>2021-2050</td>
<td>1,720</td>
<td>1,713</td>
<td>1,678</td>
<td>1,683</td>
</tr>
<tr>
<td>2071-2100</td>
<td>1,336</td>
<td>1,327</td>
<td>1,305</td>
<td>1,301</td>
</tr>
</tbody>
</table>
4. Discussion
The Ethiopian Government 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 160,000 Mm$^3$ (i.e. approximately 14x present levels and 3x the current mean annual flow at the Ethiopia-Sudan border), irrigation will exceed 360,000 ha (i.e. 23x present levels) and installed hydropower generating capacity will be in excess of 10,000 MW (i.e. 47x present levels).

Results from this study indicate that changes in climate will affect the basin hydrology. Under a mid-range climate change scenario (A1B), in a natural situation (i.e. no development), flows increase at the border, in the first half of the 21$^{\text{st}}$ 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 influences the basin runoff regime. However, even in the natural scenario, average annual flows at the border decrease by approximately 20% in the second half of the century.

The planned water resources development in the basin will cause additional reductions in flows. However, the additional decline is relatively modest. For example, under the full development scenario, the development of irrigation and hydropower results in 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 21$^{\text{st}}$ 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 (Fig. 3). 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.

![Comparison of simulated water resources development](Fig 3)
These 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, in the second half of the 21st 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.

5. Conclusion
The anticipated water resource implications of climate change are likely to have severe consequences for people and the economies of the riparian states. Harsher climate change, which, based on current emissions trends is perhaps more likely than that anticipated in the A1B scenario, would have even more severe effects. Effective water resources management is critical for successful adaptation to climate change. However, to moderate the negative impacts of climate change requires much better planning and management of water resources and, in particular, water storage. In the Blue Nile Basin, this will necessitate much greater cooperation between riparian states with much more systematic planning of water resources development. In the absence of this more systematic planning, much of the currently planned investment in water storage will fail to deliver all the intended benefits. Careful consideration needs to be given to integrated, possibly transnational, storage ‘systems’ that maximize the benefits to be obtained from the complementarities of different storage options (e.g., surface water used conjunctively with groundwater) as well as innovative solutions, such as managed aquifer recharge. However, planning for climate change requires going beyond water alone to consider other sectors in the water-energy-food nexus.

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