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IFPRI Discussion Paper 00700

May 2007

Integrated Management of the Blue Nile Basin in Ethiopia: Hydropower and Irrigation Modeling

Paul J. Block, University of Colorado

Environment and Production Technology Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE.

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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

www.ifpri.org

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ABSTRACT

Ethiopia is at a critical crossroads with a large and increasing population, a depressed national economy, insufficient agricultural production, and a low number of developed energy sources. The upper Blue Nile basin harbors considerable untapped potential for irrigation and hydropower development and expansion. Numerous hydrologic models have been developed to assess hydropower and agricultural irrigation potential within the basin, yet often fail to adequately address critical aspects, including the transient stages of large-scale reservoirs, relevant flow retention policies and associated downstream ramifications, and the implications of stochastic modeling of variable climate and climate change. A hydrologic model with dynamic climate capabilities is constructed to assess these aspects. The model indicates that large-scale development typically produces benefit-cost ratios from 1.2-1.8 under historical climate regimes for the projects specified. Climate change scenarios indicate potential for small benefit-cost increases, but reflect possible significant decreases. Stochastic modeling of scenarios representing a doubling of the historical frequency of El Niño events indicates benefit-cost ratios as low as 1.0 due to a lack of timely water. An evaluation of expected energy growth rates reinforces the need for significant economic planning and the necessity of securing energy trade contracts prior to extensive development. A Ramsey growth model for energy development specifies project multipliers on total GDP over the 100-year simulation ranging from 1.7-5.2, for various climatologic conditions.

Key Words: Ethiopia, dams, water resources development, hydrologic model, energy, climate variability, climate change

1. INTRODUCTION

Eighty-three percent of Ethiopians currently lack access to electricity, with 94 percent still relying on fuel wood for daily cooking and heating (Tegenu 2006). Ethiopia possess abundant water resources and hydropower potential, second only to the Democratic Republic of Congo in all of Africa, yet only three percent of this potential has been developed (World Energy Council 2001). Likewise, less than 5 percent of irrigable land in the Blue Nile basin has been developed for food production (Arsano and Tamrat 2005). The Ethiopian government is therefore pursuing plans and programs to develop hydropower and irrigation in an effort to substantially reduce poverty and create an atmosphere for social change. It has been shown that access to electricity, including rural electrification, is a key to poverty reduction in Ethiopia (MoFED 2006). Implementation, however, is not trivial, especially due to the large financing and investment challenges, as well as required institutional capacity.

Numerous hydrologic models have been developed to assess hydropower and agricultural irrigation potential within Ethiopia and the whole of the Nile River basin (Guariso and Whittington 1987; Levy and Baecher 1999; Geogakakos 2004; Whittington et al. 2005). These models can support the identification of suitable hydropower and irrigation projects, with implications to hydrology and economics of the entire basin. Four large-scale dams and reservoirs along the Blue Nile River within Ethiopia, as proposed by the United States Bureau of Reclamation (USBR) in 1964, are often included in these models, due to the enormity of their potential for hydropower generation and irrigation supply. This paper utilizes the IMPEND model for hydropower and irrigation analysis to address several critical aspects for which other models fail to account, including the transient stages of the reservoirs and associated downstream ramifications, varying downstream flow requirements, and the implications of stochastic modeling of variable climate and climate change during both the transient and long-term stages. These critical aspects lead to questions whose answers not only determine how but if the implementation of these dams is realistic and justifiable.

The paper begins with Blue Nile basin hydrology and climatology details, a brief depiction of the proposed USBR dams and an outline of the IMPEND model. Subsequently, model results for varying flow policies and climatic conditions are presented, including probable multipliers to the Ethiopian economy due to the influx of energy and agricultural production. The paper concludes with a summary and discussion.

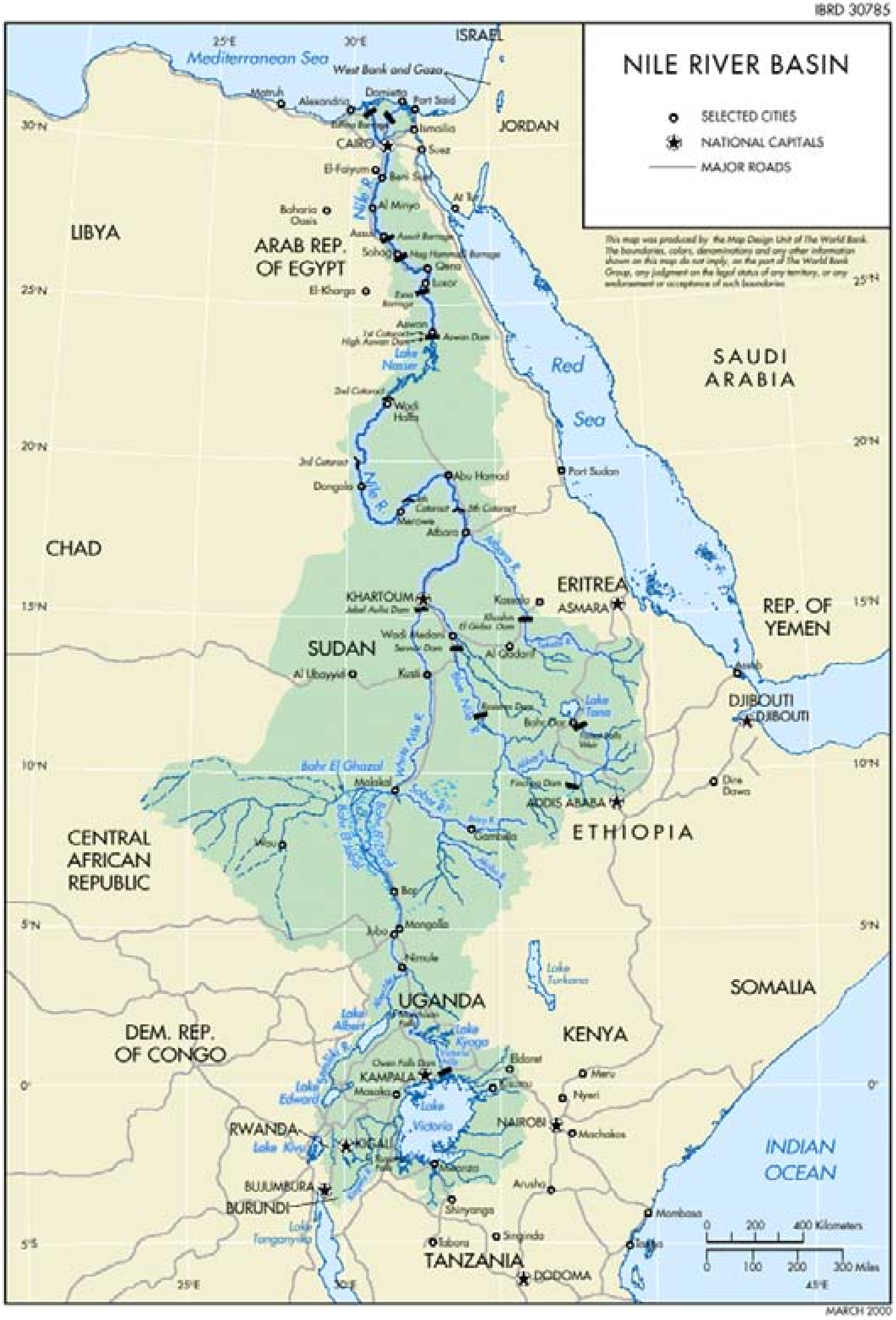
2. BLUE NILE AND NILE BASIN HYDROLOGY, CLIMATOLOGY, AND WATER ALLOCATION

The Blue Nile headwaters emanate at the outlet of Lake Tana in the Ethiopian highlands, as presented in Figure 1. It is joined by many important tributaries, draining the central and southwestern Ethiopian highlands, becoming a mighty river long before it reaches the lowlands and crosses into Sudan. It stretches nearly 850 kilometers between Lake Tana and the Sudano-Ethiopian border, with a fall of 1300 meters; the grades are steeper in the plateau region, and flatter along the low lands. From approximately 30 kilometers downstream of Lake Tana and into Sudan, the river flows through deep rock-cut channels.

Very few stream gauges exist along the Blue Nile River within Ethiopia, and those that do tend to have spotty or limited records, and are often not publicly available. Upon leaving Lake Tana, the next station location of substantial length is at Roseires in Sudan. Stations with shorter records, at Kessie, downstream of Lake Tana, and El Diem, at the Sudano-Ethiopian border, exist, but provide only a few years of monthly flows.

The climate in the Blue Nile River basin varies greatly between its inception in the highlands of Ethiopia and its confluence with the White Nile River. Lake Tana sits at 1830 meters above sea level with an annual average precipitation of nearly 1000 mm and evaporation rates of 1150 mm per year. Most of the highlands of Ethiopia, at elevations between 1500 and 3000 meters, are wet, lush and green, and have daily mean temperatures that fluctuate between 15°-18° Celsius. As the Blue Nile drops into the lowlands and into southern Sudan, rainfall decreases and evaporation increases, resulting in a significant net loss. Temperatures also increase in variability, and reach substantially higher levels than at Lake Tana. The Sennar region, located in the southeastern part of Sudan, experiences evaporation rates that total 2500 mm per year, yet only receives 500 mm of rain annually; mean daily temperatures approach 30° Celsius (Shahin 1985; Sutcliffe and Parks 1999).

Figure 1. The Nile basin



Courtesy of the World Bank

Monthly precipitation records indicate a summer monsoon season, with highest totals in the June-September months (Block and Rajagopalan 2006). Near Sennar, Sudan, rains during this season account for nearly 90 percent of total annual precipitation, while in the Ethiopian highlands, approximately 75 percent of the annual precipitation falls during the monsoon season. August is typically the peak month, with 2-3 hours of average daily sunshine and humidity levels close to 85 percent in the Ethiopian highlands (Shahin 1985; Conway 2000). Although the deserts of Sudan and Egypt receive no appreciable precipitation during the monsoon season, this intense upstream episode gives rise to the annual Nile flood, whose impacts are felt throughout the entire Nile basin.

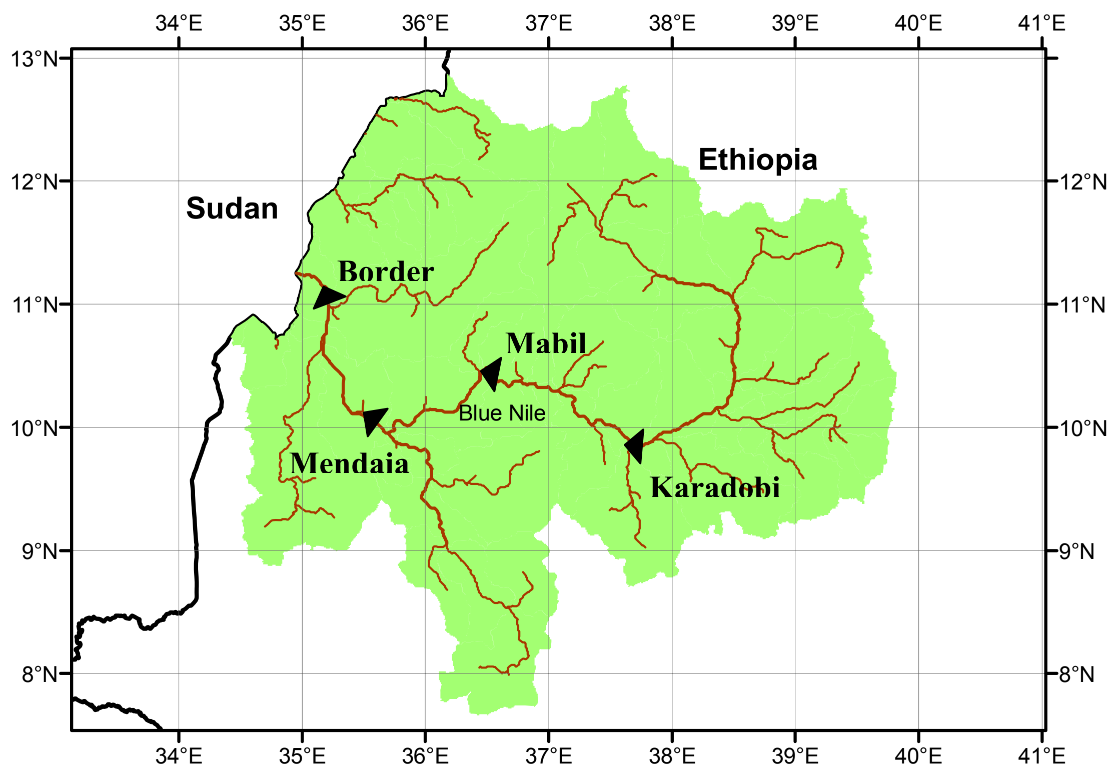
Due to its equatorial positioning, the Nile River is ripe for evaporation in its channels and reservoirs, and evapotranspiration through irrigation practices. It is estimated that tens of billions of cubic meters are lost annually from these processes.

The Nile is predominantly utilized for irrigation purposes in Ethiopia and Sudan, and for irrigation, hydropower, industrial and domestic use in Egypt, although irrigation still demands the largest portion. Although approximately 84 percent of the inflow to Lake Nasser at Aswan, Egypt initiates from Ethiopia through the Blue and Atbara Rivers, Ethiopia has limited rights to use these resources. Egypt and Sudan, through the Agreement of 1959, are allotted 55.5 and 18.5 billion cubic meters, respectively, each year, with no allotment to Ethiopia (Said 1993; Johnson and Curtis 1994). Allocation of the Nile waters has been a controversial topic for decades, and is becoming even more heated as White Nile countries gain independence and demand rights to this precious resource, pronouncing the 1959 Agreement no longer valid. In 1998, the Nile Basin Initiative was created to formulate cooperation between all countries in the Nile basin and work toward amicable alternatives and solutions for water resources benefits (Nile Basin Initiative 1999).

3. USBR PROPOSED HYDROELECTRIC DAMS AND ETHIOPIAN GOVERNMENT PROPOSED IRRIGATION DEVELOPMENT PLAN

In 1964, the USBR, upon invitation by the Ethiopian government, performed a thorough investigation and study of the hydrology of the upper Blue Nile basin. This was during the time of construction of the Aswan High Dam in Egypt (1960-1970). Included in the USBR's study was an optimistic list of potential projects within Ethiopia, including preliminary designs of dams for irrigation and hydroelectric power along the Blue Nile and Atbara Rivers. The four major hydroelectric dams along the Blue Nile, as proposed by the USBR, are presented in Figure 2.

Figure 2. Proposed hydroelectric dams along the Blue Nile in plan view, as proposed by the USBR



The Karadobi Dam and reservoir would be located just upstream of the Guder River confluence, approximately 385 km downstream of Lake Tana, and would be responsible for controlling a draining area of nearly 60,300 square kilometers. The Mabil Dam would sit 145 km further downstream, 25 km downstream of the confluence with the Birr River. The Mendaia and

Border Dams would be constructed about 175 km and 21 km upstream of the Sudano-Ethiopian border, respectively. Further dam details and characteristics are provided in Tables 1 and 2 (Bureau of Reclamation 1964). Figure 3 illustrates the designations for heights and heads from Table 1.

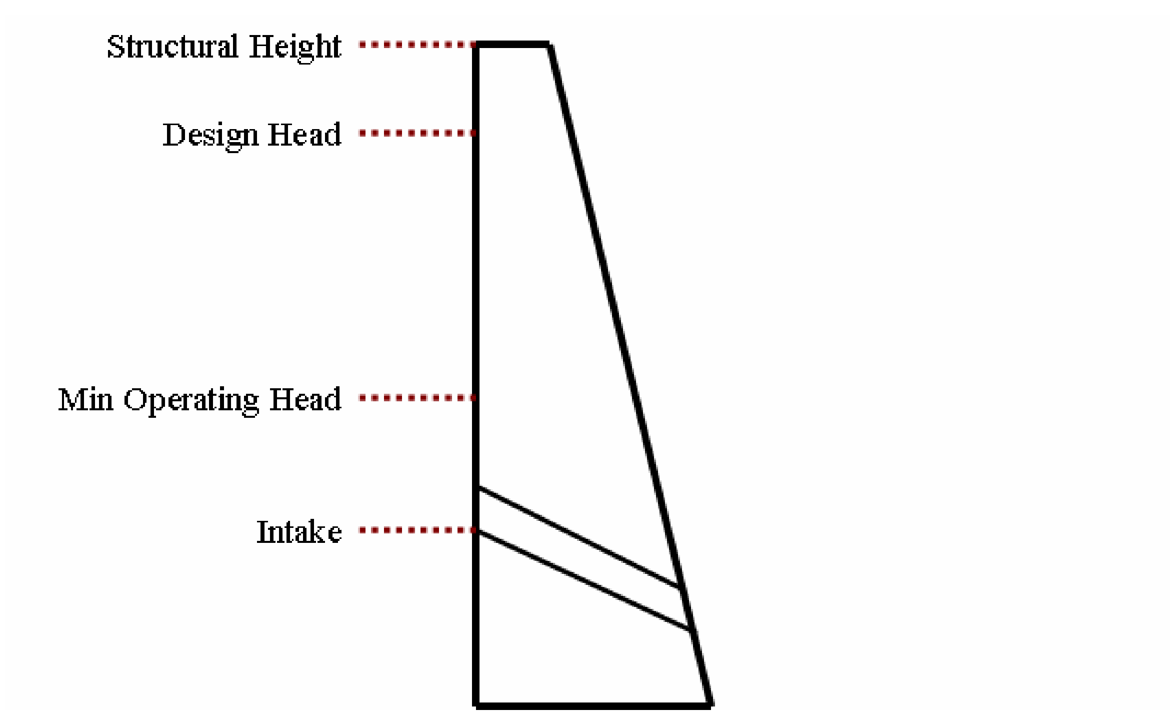
Table 1. Proposed dam characteristics.

Project Name	Structural Height (m)	Crest Length (m)	Design Head (m)	Min. Oper. Head (m)	Intake (m)
Karadobi	252	980	181.4	116	102.5
Mabil	171	856	113.6	73.8	59.7
Mendaia	164	1134	117.4	109.8	70.4
Border	84.5	1200	75	68.4	27.8

Table 2. Proposed reservoir and power characteristics.

Project Name	Reservoir Capacity (m^3)	Flow at Design Head (m^3/s)	Installed Power at Design Head (MW)
Karadobi	32.5 billion	948	1350
Mabil	13.6 billion	1346	1200
Mendaia	15.9 billion	1758	1620
Border	11.1 billion	2378	1400

Figure 3. Designations for dam heights and heads



Operating in tandem, these four dams would impound a total of 73.1 billion cubic meters, which is equivalent to approximately 1.5 times the average annual runoff in the basin. The total installed capacity at design head would be 5570 megawatts (MW) of power, about 2.5 times the potential of the Aswan High Dam in Egypt, and capable of providing electricity to millions of homes. This would be an impressive upgrade over the existing 529 MW of hydroelectric power within Ethiopia as of 2001 (Thomson Gale 2006).

Preliminary plans suggested dam construction from upstream to downstream, beginning with Karadobi and finishing with Border. More recent schemes, however, have altered the construction order to be: Karadobi, Border, Mabil, and finally Mendaia (Harshadeep 2006). This new plan attempts to capture flows leaving the country earlier in the construction timeline to take advantage of hydroelectric potential. Models and evaluations in this study incorporate the revised order.

The Ethiopian Ministry of Water Resource's 2002 Irrigation Development Plan recommends expansion of irrigated cropland along the western border region. The plan incorporates approximately 250,000 hectares, or 35 percent of the estimated total irrigable land in the Blue Nile basin (Arsano and Tamrat 2005). Releases for irrigation are therefore assumed to be from the Mendaia and Border reservoirs only, which would be constructed in the vicinity of the targeted irrigation area. The Ethiopian irrigation plan includes approximately equal areas of small-scale and large-scale irrigation development, although no distinction between these two is made here. Withdrawals from the deep rock-cut channel reservoirs may not be an easy feat, likely involving significant pumping costs, but have been assumed as a plausible opportunity.

4. IMPEND MODEL FRAMEWORK

The Investment Model for Planning Ethiopian Nile Development (IMPEND) is a standalone optimization model, written in GAMS, requiring a single input file including streamflow and net evaporation at the four dam locations and Roseires, Sudan (Block 2006). The model thus encompasses the Blue Nile River from its headwaters at Lake Tana to the Roseires Dam, just beyond the Sudano-Ethiopian border. The current version weighs the tradeoff value of hydropower, at 8-cents per kilowatt-hour (as utilized in Whittington et al. 2005), and water for irrigation, producing crops estimated at $325 per hectare (FAOSTAT 2006; Diao et al. 2004), with the total present worth of benefits as the objective value. Viable outcomes may include allocating all water resources to hydropower or irrigation for consumptive use, or, more likely, to a combination of the two. User specified stipulations on the minimum allowable downstream flow (at Roseires) also regulate the model. The time frame simulated is adjustable, but held constant at 30 years for the transient portion of this analysis. Extensions for benefits to 100 years are also computed, resulting in a time period of 2000-2099.

A noteworthy feature of IMPEND is its perfect foresight ability. For any given run, the model will produce the absolute best (largest) objective value possible. This is analogous to operating the system of dams and irrigation perfectly, as if privy to all future streamflow and climate information. While this methodology may ultimately be unrealistic, it does allude to the full potential of a given scenario, and provides a consistent framework for comparison between scenarios.

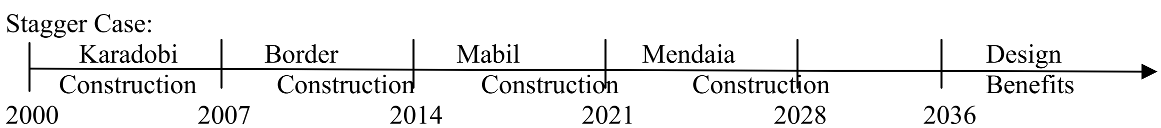
Optimization of electric energy is formulated around the head level in each reservoir. All operational aspects are nonlinear functions of head, including the reservoir storage, reservoir surface area for determining evaporative losses, the quantity of water released through the turbines, turbine efficiency, and reservoir spilling. These functions have been derived from either relationship curves in the preliminary USBR report, or typical relationships based on site specific characteristics.

A final important characteristic of IMPEND is the flexibility in interest rates and downstream flow policies. The interest (or discount) rate may be set at any value for use in determining the present net value of hydropower and irrigation benefits. Obviously, the model will respond differently to a scenario depending on the level of discounting. The downstream flow constraint is established at the entrance to Roseires dam. The constraint functions to not only prescribe how the proposed Ethiopian reservoirs may be filled (timing and quantity) and the optimal allotment to irrigation, but also allows for assessment of the potential impact on downstream countries. The flow constraint in IMPEND may follow one of two policies. The first policy allows for a share of the annual flow (passing the Sudano-Ethiopian border) to be retained within Ethiopia (5 percent in this study), with the balance reaching Roseires. The second policy allows for streamflow to be impounded within Ethiopia for annual flows (again, at the border) above a given threshold, based on the historical record (above the 50th percentile [median] of historical flows for this study.) According to this policy, only in years in which the threshold is exceeded may water be retained, in which case the entire excess may be withheld. Both of these policies represent plausible scenarios for retaining water within Ethiopia, but it is worth noting that neither is presently acceptable under the current agreements with Sudan and Egypt.

The time horizon, albeit adjustable, is assumed to be 100 years, 2000-2099, for all scenarios. This includes a period of construction of seven years (2000-2006) for the first dam and three years (2004-2006) for the irrigation system before any benefits may be realized. The 30-year transient portion of the model thus starts at 2007, when water may first be impounded, and continues until 2036. Full benefits may or may not be reached at this point, depending upon hydrologic conditions. Benefits beyond 2036 are assumed to be constant at the design level. This assumption may be a slight under or over approximation, but is deemed appropriate, as the present net benefits beyond 36 years becomes relatively small for most discount rates.

For this study, the dams are presupposed to come online in seven year intervals. Figure 4 illustrates the timeline.

Figure 4. General schematics of IMPEND stagger timeline



Benefits for each dam may begin post-construction of that dam. Full benefits for each dam may or may not be reached in the transient period, again, depending upon hydrologic conditions.

Relevant climate scenarios for streamflow and net evaporation along the upper Blue Nile River include analyses based on historical (1961-1990) data, as well as potential climate change scenarios. El Niño Southern Oscillation (ENSO) events have been shown to have significant influence in the upper Blue Nile region, producing wetter conditions under La Niña and drier conditions under El Niño. Analyses of future climate change, though, do not give a clear indication of expected conditions in the basin; literature specifies that climate change may result in an increase in either El Niño or La Niña events (IPCC 2001; Conway 2004). The climate change scenarios, therefore, address the possibilities of doubling the frequency of El Niño or La Niña events. An ensemble approach, generating 50 plausible climate scenarios for stochastic analysis of historical and ENSO based scenarios, is also employed.

5. DAM AND IRRIGATION CONSTRUCTION AND OPERATION COSTS

The dam and irrigation costs are external to IMPEND, but connected through a post-processing arrangement for the generic 2000-2099 time period. The predominant purpose for inclusion is benefit-costs analysis. Costs have been updated to the start year (2000) and are described in the following paragraphs.

Preliminary costs for each dam and associated appurtenances are included in the USBR study. These costs consist of the initial one-time construction fee (labor and materials) and annual costs, including operation and maintenance, scheduled replacement, and insurance. Initially listed in 1964 Ethiopia dollars, the figures have been updated to 2000 U.S. dollars, using a conversion rate of 2.5 Ethiopian dollars to 1 U.S. dollar (Global Financial Data 2006) and a dam cost index ratio of 0.19, implying a nearly 5-fold increase of costs (US Army Corps of Engineers 2006). Table 3 lists the initial and annual costs for each dam site in 2000 U.S. dollars.

Table 3. Construction and operation costs for dams

Project Name	Initial Construction Costs (US$ million)	Annual Costs (US$ million)
Karadobi	$ 2,213	$ 15.9
Mabil	$ 1,792	$ 13.5
Mendaia	$ 2,114	$ 17.9
Border	$ 1,985	$ 17.2

The initial costs for each dam are distributed over seven years, as displayed in Table 4. All annual costs begin in the first year post-construction, when dam benefits may be realized.

Table 4. Distribution of costs for initial dam construction

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
10%	15%	20%	20%	20%	10%	5%

Irrigation construction costs for the 250,000 hectares are estimated at one US$ 1 billion, or US$ 4,000 per hectare (Inocencio 2005; Diao et al. 2004). These costs are distributed evenly over three years, 2004-2006, to coincide with the beginning of the transient period (2007) for relevant scenarios. If deemed optimal by IMPEND, all 250,000 hectares may be irrigated beginning in 2007.

It is important to note that the above costs reflect estimated labor, materials, and annual costs, but do not include a provision for additional security for construction in an unstable region.

If security becomes an issue, costs may escalate substantially, with estimates ranging from a 25-100 percent increase, depending on the severity of security concerns (Chinowsky 2006). For this study, only the original estimates are considered, but clearly the benefit-cost ratios would be reduced if security deteriorated.

Another issue not considered in this study, but worth mentioning, is the potential for this large-scale project to create an environment of micro-inflation during the construction period. It is certainly plausible that an influx of skilled workers to the region could pump significant money into the local economy, resulting in a greater disparity in wages, increasing the overall standard of living and inflation, and then producing a vacuum post-construction, once the skilled laborers left. As serious as this may be, external costs and benefits to the project are typically not considered in analysis by organizations such as the World Bank (Rosegrant 2006).

6. MODEL RESULTS AND DISCUSSION

An endless number of scenarios can be constructed for assessing hydropower and irrigation optimization in the Blue Nile basin, including variations in flow policies, interest rates, climatic conditions, the timing of bringing dams online, etc. For an ensemble approach of 50 climatic members, with two flow policies, four interest rates, three climate conditions, and two timing states, this quickly soars to 2,400 model runs! Therefore, the number of scenarios for this study was selectively pared down with the intention of adequately scoping a relevant range of possibilities that could inform policy and planning decision-making.

Historical and climate change scenario results

It is imperative to assess results founded on historical or potential climate change, be it to a wetter or drier state, especially considering the intended longevity of the project. Table 5 presents benefit-cost (b-c) ratios for varying historical and potential climate conditions, including costs and benefits from both hydropower generation and irrigation development. These varying climate conditions have been imposed on IMPEND for the transient period only (2007-2036), when the flow policies are in effect. For the remaining years until 2099, it has been assumed that design energy and full irrigation for agriculture are achieved annually.

Table 5. Benefit-cost ratios for two flow policies for historical and climate change scenarios

Scenario:	*Historic*	*2 x La Nina*	*2 x El Nino*
Flow Policy			
5% Policy	1.48 - 1.72	1.49 - 1.76	1.43 - 1.66
50% Policy	1.18 - 1.82	1.41 - 1.91	1.07 - 1.63

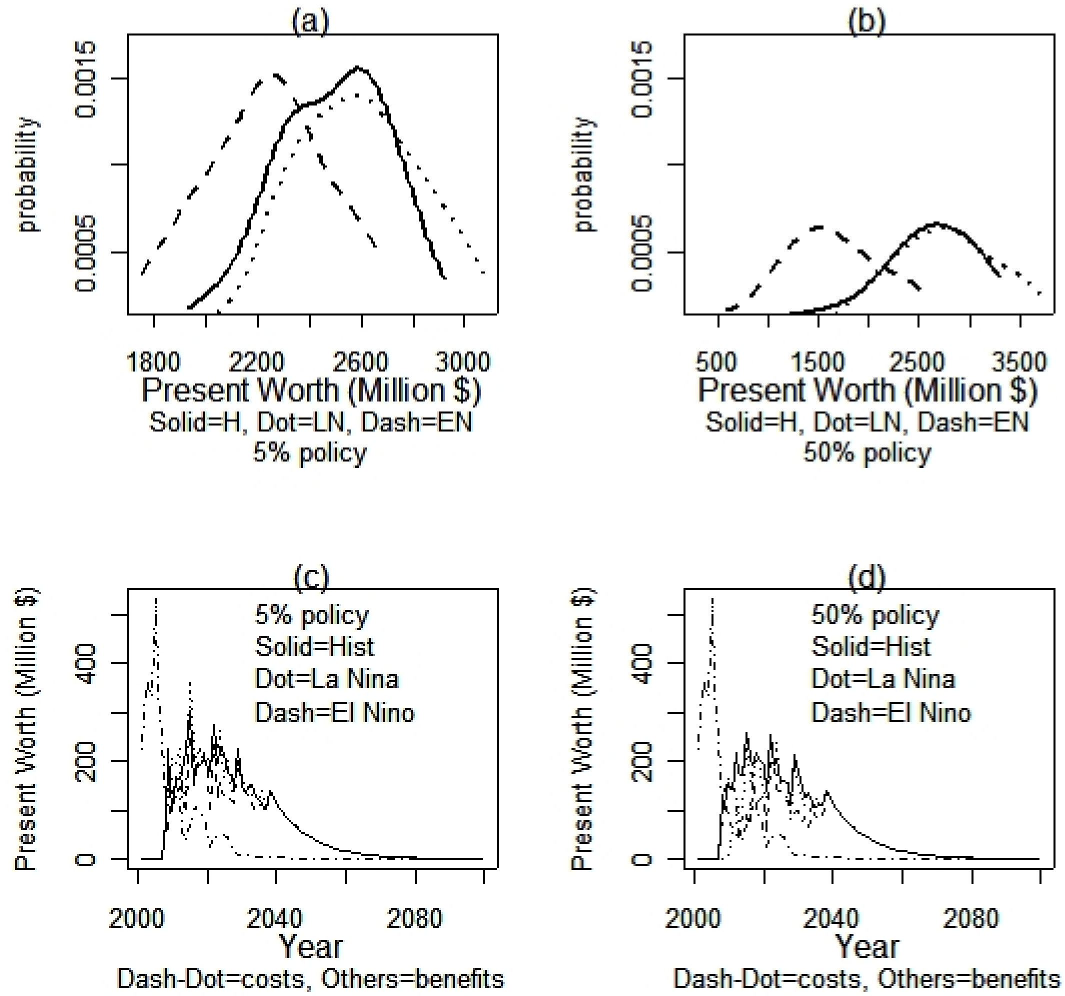
Note: Interest rate is 10%

The expected b-c ratios for a doubling of La Niña are approximately equal to those of the historic ensemble for the 5 percent policy, but slightly better for the 50 percent policy, due to generally wetter conditions. In contrast, the El Niño ensembles produce noticeably lower b-c ratios compared to the historical ensembles, due to drier conditions, resulting in less opportunity for water-related benefits. This is especially obvious in the 50 percent flow policy scenario in which one of the El Niño ensemble members plummets to a b-c ratio just above 1.0. This is a direct result of not only generally drier conditions, but also a lack of timely water (i.e. numerous early dry years) and clearly represents conditions in which construction of the hydropower and irrigation projects may not prove worthwhile. In actuality, the b-c ratios for the doubling of El

Niño may well be an overestimation, as the likelihood of achieving design benefits for irrigation and hydropower beyond the transient stage is small.

Figures have been created for visual representation, including present worth and energy output for the historical, La Niña, and El Niño ensembles. Figures 5a and 5b compare the Probability Density Functions (PDFs) of net present value for all three ensembles under the two flow policies. As reflected in Table 5, the El Niño PDFs are noticeably lower than the historical PDFs, and the La Niña PDFs are approximately equal to the historical PDFs. Figures 5c and 5d contrast present net value costs and benefits for a sample ensemble member. The cost curve is also included. Again, as expected, the El Niño benefit curve is lower than the other two benefit curves for much of the transient period; the La Niña benefit curve is similar to the historical benefit curve.

Figure 5. PDFs of net present worth for the historic (H), La Niña (LN), and El Niño (EN) ensembles under the (a) 5 percent and (b) 50 percent flow policies

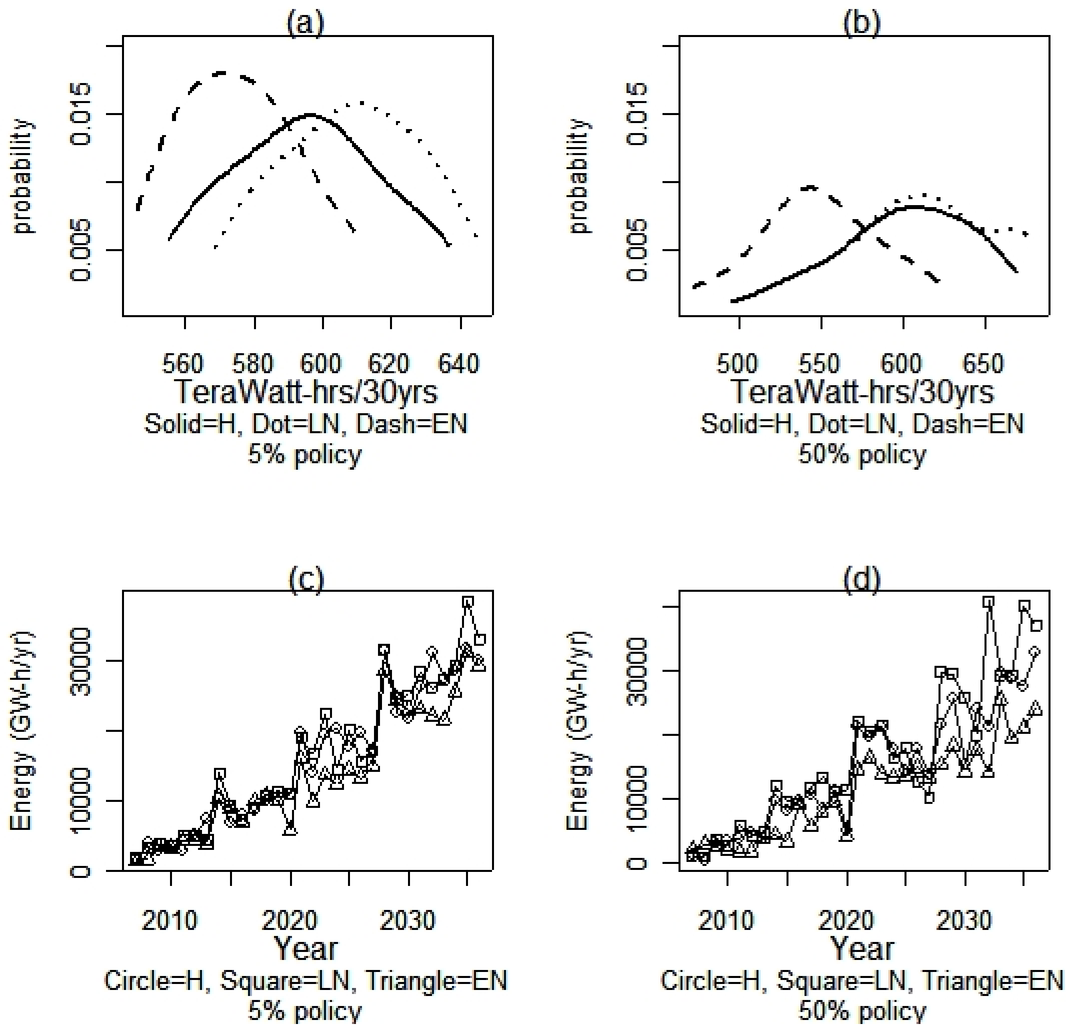


Note: Annual benefit and cost present worth curves under the same three ensembles for the (c) 5% and (d) 50% flow policies

Both the (c) and (d) cases represent the identical historical ensemble member.

Figure 6 presents energy production results for the same ensembles, and illustrates comparable findings to Figure 5. Using an industrial growth rate of 6 percent (CIA 2006), Ethiopia would be unable to domestically absorb as much as could be generated, reinforcing the need for significant economic planning and the necessity of securing energy trade contracts prior to extensive development.

Figure 6. PDFs of total energy produced for the historic (H), La Niña (LN), and El Niño (EN) ensembles under the (a) 5 percent and (b) 50 percent flow policies during the transient period

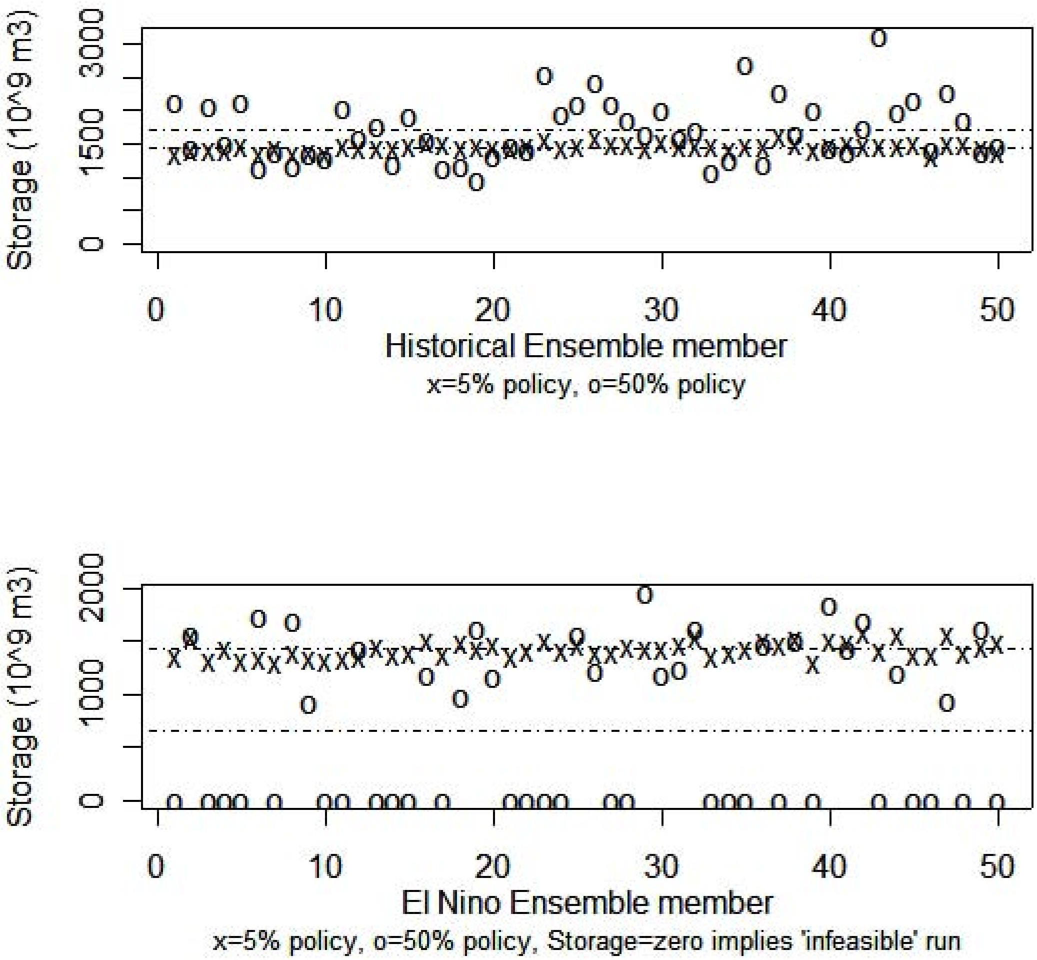


Note: Annual energy production under the same three ensembles for the (c) 5 percent and (d) 50 percent flow policies during the transient period.

Both the (c) and (d) cases represent the identical historical ensemble member.

Not all members of the El Niño ensembles produce feasible results in IMPEND under the 50 percent flow policy case. These results have been eliminated from the analysis. It is paramount, though, to realize that the prospects of infeasibilities are real, due to lack of water availability and timeliness. Infeasibilities are typically a result of early dry years or successive dry years, when no water may be impounded, yet large evaporative demands and downstream requirements must still be met. Figure 7 illustrates cumulative storage for the first ten years of each historical and El Niño ensemble member run through IMPEND for the 5 percent and 50 percent flow policies. The dashed lines represent ensemble means. Any storage equal to zero implies an infeasible run.

Figure 7: Cumulative storage for the first ten years of each historical (top) and El Niño (bottom) ensemble member for the 5 and 50 percent flow policies.



The dashed lines represent ensemble means. Any storage equal to zero implies an infeasible run.

The 5 percent flow policy storage results are quite tightly grouped, as expected, due to the annual assurance of water. For the 50 percent flow policy, no infeasibilities are generated in the historical ensemble; just over half of El Niño ensemble members, however, are infeasible. This coincides with the fact that annual streamflow for two thirds of all years in the El Niño ensemble fall below the historic 50^{th} percentile. Obviously this flow policy does not perform well under dry conditions, and is not preferable if runoff and discharge might decrease over time as a result of climate change. However, due to its slightly superior performance for wetter conditions, this policy should not be completely eliminated from consideration.

Climate change influences could play a major role in determining the success or failure of the proposed hydropower and irrigation project. Overall, the 5 percent flow policy appears to be more robust to modeled climate changes than the 50 percent flow policy. It consistently outperforms the 50 percent flow policy in drier conditions, and is nearly on par with it in wetter conditions.

Irrigation versus hydropower

As previously mentioned, irrigation and hydropower benefits have thus far been lumped together for analysis. The two work in complimentary fashion in IMPEND by reason of the downstream diversion location for irrigation. This allows the water to remain in the hydropower system as long as possible, yet still be utilized for crops. In the historical and La Niña scenarios, hydropower and irrigation are almost always both maximized, implying complementarities rather than tradeoffs. Irrigation b-c ratios are generally quite close to 1.0. However, for drier conditions, such as the El Niño scenario, IMPEND opts to reserve water for hydropower generation and forego crop irrigation in order to meet downstream flow requirements. For the El Niño 5 percent flow policy, the number of hectares irrigated in the very early years may not attain the 250,000 hectare maximum due to the generally drier conditions, but grows quickly afterward, typically reaching the maximum level within a 2-4 year period. For the El Niño 50 percent flow policy, though, it is common for no irrigation to take place during the transient stage, or for spotty irrigation, which is not especially helpful for cropland management and planning, and consequently contributes to b-c ratios below 1.0. Understandably, a surge in crop yields or commodity prices, associated with a lessening in demand for energy or energy value may reverse these trends. Other political decisions, for example, national food security, might also favor irrigation over the energy development strategy.

Project multipliers

To assess the influence of the proposed hydropower project on the Ethiopian economy as a whole, a series of Ramsey economic growth models are developed. The basic premise of the model is to balance capital, labor, and the energy sector (collectively constituting gross domestic product) with consumption and investment; irrigation has not been included. Equation 1 presents the key relationship:

$$A * L_t^{\alpha} * K_t^{\beta} * E_t^{\gamma} + ET_t = c_t + i_t + IE_t \qquad (1)$$

A is a calibration parameter to rectify units, and *t* is the time step, in months. *L* represents the labor force, initially equal to 37.5 million, growing at a rate consistent to the population growth rate of 2.9 percent per year (CIA 2006). *K* is the capital within the country, initially set at US$ 16.5 billion (UNECA 2000), growing with investment. *E* symbolizes the domestic energy sector, set to 4,643 GWh in the base year, and represents energy that is consumed by Ethiopia, while *ET* represents energy generated beyond the country's ability to absorb, available for trade to neighboring countries. The exponents represent the value share, and follow a Cobb-Douglas approach summing to 1.0 (Mansfield and Yohe 2004). For this model, α, β, and γ are set to 0.446, 0.48, and 0.074, respectively. *c* stands for the country-wide consumption, and *i* the investment. *IE* represents specific investment in the energy sector (infrastructure and associated costs.)

Equation 2 demonstrates the objective function of the model, to be maximized.

$$U = \sum_t \left[d_t * \log(c_t) \right] \tag{2}$$

U symbolizes the country-wide utility, and *d* the discount factor.

The project multipliers derived here represent a multiplier on gross domestic product (GDP) over the 100-year simulation, and provide an indication of the potential benefits of the project, including associated benefits through economic feedbacks. They result from a combination of the total gross domestic product (discounted from Equation 1) from these Ramsey growth models utilizing energy from IMPEND or prescribed energy growth. Equation 3 presents the relationship (Yohe 2006).

$$Multiplier = \frac{TotalGDP_{(IMPEND)} - TotalGDP_{(\mathrm{Pr}escribed)}}{PW_{(IMPEND)}} \tag{3}$$

The numerator represents the difference between the total GDP from the Ramsey model using energy from IMPEND (first term) and prescribed energy (second term.) *PW* represents the present worth of the hydropower project, discounting benefits and costs. The Ramsey model utilizing prescribed energy includes *ET* and *IE* values set to zero (no excess energy produced and no massive energy investment costs.) The objective is to evaluate if Ethiopia's economy is better off with or without the implementation of the hydropower project. A multiplier greater than 1.0 indicates economic growth if the project is realized; less than 1.0 implies that the project may not be economically wise. To reiterate, the multiplier is not simply a benefit-cost ratio of the hydropower project, but reflects the potential impact of significantly increasing the size of the energy sector on the total GDP.

The following tables present expected multipliers for the three climatic conditions under the two flow policies. Table 6 assumes a prescribed growth rate in energy demand of zero percent; Table 7 assumes a 3 percent prescribed energy growth rate.

Table 6. Multipliers on total GDP utilizing IMPEND and zero percent prescribed energy models

Scenario:	*Historic*	*2 x La Nina*	*2 x El Nino*
Flow Policy			
5% Policy	4.3	4.2	5.0
50% Policy	4.3	3.8	5.2

Table 7. Multipliers on total GDP utilizing IMPEND and 3 percent prescribed energy models

Scenario:	*Historic*	*2 x La Nina*	*2 x El Nino*
Flow Policy			
5% Policy	1.9	1.9	2.2
50% Policy	1.9	1.7	2.3

Clearly all ranges of multipliers are well above 1.0, indicating the potential positive impact of the hydropower project on the economy as a whole. The values for the El Niño condition are slightly higher based on lower overall net present values, but may indicate a greater overall risk. An evaluation of energy traded (*ET*) to neighboring countries indicates a strong potential for boosting the Ethiopian economy, and reinforces the need for significant economic planning including the necessity of securing energy trade contracts prior to extensive development.

7. CONCLUSIONS AND DISCUSSION

Numerous hydrologic models have been developed to assess hydropower and agricultural irrigation potential within the upper Blue Nile basin, yet often fail to adequately address critical aspects, including the transient stages of large-scale reservoirs, relevant flow retention policies and associated downstream ramifications, and the implications of stochastic modeling of variable climate and climate change. The IMPEND hydrologic model with dynamic climate capabilities is constructed to assess these aspects. Climate change scenarios, represented by changes in the frequency of El Niño and La Niña events, indicate potential for small benefit-cost increases, but also reflect the potential for noteworthy decreases, relative to historical climate conditions. Stochastic modeling of scenarios representing a doubling of the historical frequency of El Niño events indicates benefit-cost ratios as low as 1.0, with numerous runs producing potentially infeasible hydropower/irrigation projects due to a lack of timely water. Project multipliers on total GDP over the 100-year simulation range from 1.7-5.2 for various climatologic conditions for consideration of the hydropower project only.

Although considerable effort has been devoted to creating as comprehensive and accurate a model as possible, IMPEND is only as good as the data it is supplied. The Blue Nile within Ethiopia remains largely ungauged, and a certain degree of uncertainty has to be factored into the use of specific hydrologic and climatic conditions. Undoubtedly, site-specific testing and modern technology will alter USBR plans, possibly changing the potential or overall scope of hydropower and irrigation development. Among this uncertainty, though, the results of this study are thought to be representative of prospective future hydropower and irrigation development scenarios, and at the least give an indication of the feasibility under varying conditions.

The commencement of water resources planning and strategizing with downstream riparian countries is vital to the success of the hydropower and irrigation development projects. There are many opportunities for win-win situations, with bargaining chips including energy and food production, regulated streamflow, water conservation through reduced evaporation losses, and redistributed water rights through a renegotiation of the 1959 Agreement, to name a few. Some progress in this direction has been made since the start of the Nile Basin Initiative.

Additional aspects and scenarios not considered in this study also warrant further attention and analysis with IMPEND. The model could be modified to create more realistic reservoir operations by looking at a smaller time window, perhaps on an annual basis, without the benefit of perfect foresight providing streamflow knowledge of the entire scenario. This may be accomplished by solving the model yearly with the expectation that the following year would produce average hydrologic conditions. In a separate variation, a form of the precipitation forecast model developed in Chapter 6 could be directly tied to IMPEND to guide reservoir operations on a continuing basis. A third approach may be to condition reservoir operations based on current hydrology and a *K-nn* weather generator for the relevant climatic condition to reflect potential future changes.

The inclusion of supply and demand curves into IMPEND, both for hydropower and agriculture, may also prove valuable. This would provide a dynamic aspect to reflect pricing and availability, which would undoubtedly change throughout the project life. Additionally, the curves could also play a key role in the assessment of varying climatic conditions, as marginal prices may be noticeably different between scenarios. Including specific crop types and respective irrigation requirements would also increase the IMPEND level of detail.

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IFPRI HEADQUARTERS

2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

IFPRI ADDIS ABABA

P. O. Box 5689
Addis Ababa, Ethiopia
Tel.: +251 11 6463215
Fax: +251 11 6462927
Email: ifpri-addisababa@cgiar.org

IFPRI NEW DELHI

CG Block, NASC Complex, PUSA
New Delhi 110-012 India
Tel.: 91 11 2584-6565
Fax: 91 11 2584-8008 / 2584-6572
Email: ifpri-newdelhi@cgiar.org