Economic Analysis of Large-Scale Upstream River Basin Development on the Blue Nile in Ethiopia Considering Transient Conditions, Climate Variability, and Climate Change

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Abstract: The upper Blue Nile Basin in Ethiopia harbors considerable untapped potential for irrigation and large-scale hydropower development and expansion. Numerous water resources system models have been developed to evaluate these resources, yet often fail to adequately address critical aspects, including the transient (e.g., filling) stages of reservoirs, relevant streamflow retention policies and downstream consequences, construction staggering, and the implications of stochastic modeling of variable climate and climate change. This omission has clear economic impacts on benefits and costs and could be pivotal in national policy and decision making. The Investment Model for Planning Ethiopian Nile Development dynamic water resources system model is outlined and applied to address these aspects. For the hydropower and irrigation development projects specified, model results disregarding transient and construction stagger aspects demonstrate overestimations of $6 billion in benefits and 170% in downstream flows compared to model results accounting for these aspects. Benefit-cost ratios for models accounting for transient conditions and climate variability are found to range from 1.2–1.8 under historical climate regimes for the streamflow retention policies evaluated. Climate change scenarios, represented either by changes in the frequency of El Niño and La Niña events or by the Special Report on Emissions Scenarios projections, indicate potential for small benefit-cost increases, but also reflect the potential for noteworthy decreases, relative to the historical climate conditions. In particular, stochastic modeling of scenarios representing a doubling of the historical frequency of El Niño events indicates benefit-cost ratios as low as 1.0, even under perfect foresight optimization modeling, due to a lack of timely water. However, even at this ratio, Ethiopia, at current growth rates, may still be unable to absorb all the potential energy developed, reinforcing the need for significant economic planning and the necessity of securing energy trade contracts prior to extensive expansion.

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Introduction

Ethiopia is at a critical crossroads with a burgeoning population, a depressed national economy, insufficient agricultural production, and a minimal number of developed energy sources. The Ethiopian government is therefore pursuing plans and programs to develop hydropower and irrigation in an effort to bolster these sectors. Major development strategies include four large-scale hydroelectric dams along the upper Blue Nile River and 250,000 ha of irrigated cropland along the western border [Bureau of Reclamation 1964; Water Resources Development Programme (WRDP) 2001; Arsano and Tamrat 2005].

Numerous water resources system 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; Georgakakos 2007; Whittington et al. 2005). These models are designed to support the identification of suitable projects, with implications to water resources and economics of the entire basin. Often, the four dams (Karadobi, Mabil, Mendaia, and Border, upstream to downstream) and irrigation development projects are explicitly included. While these models are enlightening, there appear to be several critical aspects they do not incorporate that may have serious implications on future decisions, especially given the Nile's transboundary state. These aspects include the transient, or filling, stages of the reservoirs, streamflow retention policies and associated downstream consequences, construction staggering, and the implications of stochastic modeling of variable climate and climate change. This omission has clear economic impacts on benefits and costs and could be pivotal in national policy and decision making.

Disregarding downstream flows during reservoir construction

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and filling stages for large-scale upstream projects leads to nontrivial overestimation of benefits. Reduced flows in the early stages of a project may result in high costs to downstream users as well as the developing country, as little discounting has occurred. Disregarding the transient stage during planning may be potentially catastrophic, as learned from the development in the Euphrates-Tigris Basin. Tensions between Turkey, Syria, and Iraq have often been high in the past decades regarding the passage of water, to the point of amassing military troops along respective borders or threats of bombing existing dams (Naff and Matson 1984; Cohen 1991). The filling of the Ataturk Dam by the Turks in 1990 is notoriously famous for heightened conflict; both Syria and Iraq accused Turkey of failing to notify them of their plans, instigating significant downstream damage. Turkey, however, insisted that the established protocol was followed. It is highly unlikely that such costs or lost benefits were accounted for prior to development, rendering the economic analysis flawed.

Equally important for consideration are climate variability and long-term climate change. The former is routinely a critical feature of proper water resources planning, however climate change has yet to create broad inroads into water resources decision making. While climate change is the source of considerable ongoing research, explicit application to water resources development has yet to reach its full potential. Given the hydropower development life cycles on the order of 50 plus years, future benefits, both in early transient and long-term steady states, will clearly be affected. Regardless of whether expected benefits may rise or fall due to climate change, long-term planning and management becomes much more compelling given improved understanding.

The focus of this study is to construct and evaluate findings from a model able to assess the influence of the transient and long-term periods of the proposed development, under varying economic, flow policy, construction, and climatic conditions. These critical aspects assist in determining not only how the project may best proceed, but ultimately if the implementation of these dams is realistic and justifiable. This paper begins with a general description of the basin hydrology, climatology, project development, and an outline of existing basin models. A description of the dynamic hydropower-irrigation systems model for the Blue Nile proposed here, including relevant data input sources and climate change scenarios, follows. Model results and policy implications are presented and discussed next, including modeling with and without transient conditions, climate variability and change influences, and a reservoir evaporation evaluation. The paper closes with a summary and conclusion.

Ethiopia and the Nile: Hydrology, Climatology, and Project Development

Ethiopia possess abundant water resources and hydropower potential, second only to the Democratic Republic of Congo in all of Africa, yet only 3% of this potential has been developed (World Energy Council 2001). Likewise, less than 5% of irrigable land in the Blue Nile Basin has been developed for food production (Arsano and Tamrat 2005). Currently, 83% of Ethiopia's population lacks access to electricity, with 94% still relying on fuel wood for daily cooking and heating (Tegenu 2006). 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 [Ministry of Finance and Economic Development (MoFED) 2006]. Implementation, however, is not trivial, especially due to the large financing and investment challenges, as well as required institutional capacity.

The Blue Nile headwaters emanate at the outlet of Lake Tana in the Ethiopian highlands. 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 km between Lake Tana and the Sudan-Ethiopia border, with a fall of 1,300 m; the grades are steeper in the plateau region, and flatter along the low lands. 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 of substantial length is at Roseires in eastern Sudan, just across the Ethiopian border.

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 1,830 m above sea level with an annual average precipitation of nearly 1,000 mm and evaporation rates of 1,150 mm per year. Most of the highlands of Ethiopia, at elevations between 1,500 and 3,000 m, are wet, lush, and green, and have daily mean temperatures that fluctuate between 15–18°C, with rainfall totals similar to Lake Tana. As the Blue Nile drops into the lowlands and into southern Sudan, rainfall decreases and evaporation increases, resulting in a significant net surface 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 near Roseires, experiences evaporation rates that total 2,500 mm per year, yet only receives 500 mm of rain annually; mean daily temperatures approach 30°C (Shahin 1985; Sutcliffe and Parks 1999).

Monthly precipitation records indicate a summer monsoon season, with highest totals in the June to September months (Block and Rajagopalan 2007). Near Sennar, Sudan, rains during this season account for nearly 90% of total annual precipitation, while in the Ethiopian highlands, approximately 75% of the annual precipitation falls during the monsoon season. August is typically the peak month, with 2–3 h of average daily sunshine and humidity levels close to 85% in the Ethiopian highlands (Shahin 1985; Conway 2000). The El Niño-southern oscillation (ENSO) phenomenon is a main driver of the interannual variability in seasonal precipitation in the basin, with El Niño (La Niña) events generally producing drier (wetter) than normal conditions (Block and Rajagopalan 2007). 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. Climatological monthly streamflow at Roseires, Sudan, is illustrated in Fig. 1.

The Nile is predominantly used 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% of the inflow to Lake Nasser at Aswan, Egypt, initiates from Ethiopia via multiple rivers, Ethiopia has limited rights to use these resources. Egypt and Sudan, through the Agreement of 1959, are allotted 55.5 billion and 18.5 billion (10^9) m^3, 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 coun-

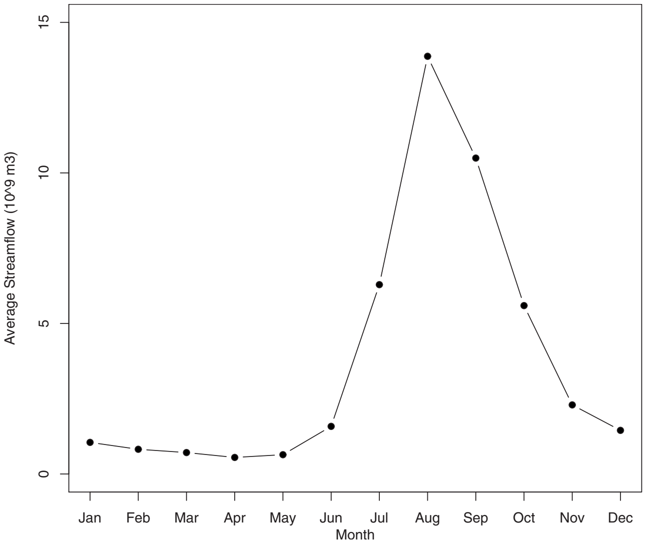

Fig. 1. Mean monthly streamflow at Roseires, Sudan, 1961–1990

tries increasingly 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).

In 1964, the U.S. Bureau of Reclamation (USBR), upon invitation from 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 Fig. 2. In addition to hydroelectric power, the dams and reservoirs would also provide benefits of irrigation sources, regulated flood waters to downstream riparian countries, and less potential evaporation compared to storage in Sudan or Egypt.

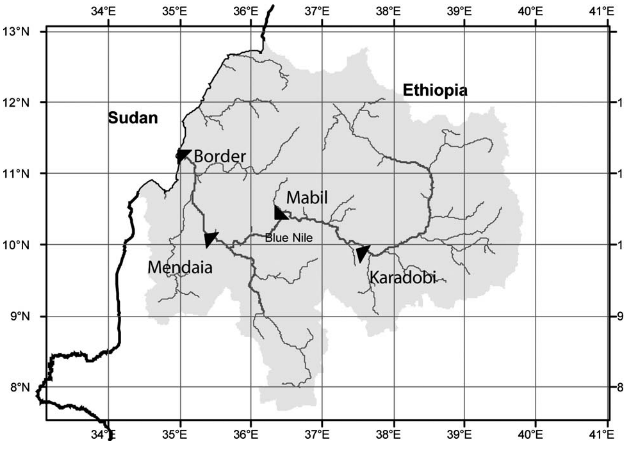

Fig. 2. Plan view of proposed hydroelectric dams along the Blue Nile, as proposed by the USBR

Operating in series, these four dams could impound a total of 73.1 billion m^3, which is equivalent to approximately 1.5 times the average annual runoff in the basin. The total installed capacity at design head would be 5,570 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). Initial construction costs range from $1.8 billion–$2.2 billion per dam; annual costs (operation and maintenance, scheduled replacement, and insurance) begin in the first year postconstruction and range from $12.5 million–$17.9 million (10^6) (Bureau of Reclamation, U.S. Department of Interior 1964).

The Ethiopian Ministry of Water Resource's 2002 Irrigation Development Plan recommends major expansion of irrigated cropland along the western border region. The plan incorporates approximately 250,000 ha, or 35% of the estimated total irrigable land in the Blue Nile Basin (WRDP 2001; Arsano and Tamrat 2005). Releases for irrigation are therefore assumed to initiate from the Mendaia or Border reservoirs only, due to their proximity to the targeted irrigation area. Irrigation construction costs for the total area are estimated at $1 billion, or $4,000 per hectare (Inocencio et al. 2005; Diao et al. 2005); irrigation infrastructure and Border Dam construction are assumed to occur simultaneously. The entire irrigable area is presupposed to be accessible upon water availability.

Existing Water Resources System Models

A number of studies have considered the development of the four USBR proposed dams by modeling their steady-state conditions. In their preliminary design, the USBR performed an operations study over a 7-year period, assuming the dams had been operational for 50 years. A water balance model for the dams in series was computed to demonstrate the regulated flow conditions in comparison to the natural flow, illustrating the sharp reduction in peak flow during the summer months (Bureau of Reclamation, U.S. Department of Interior 1964).

Guariso and Whittington (1987) also developed a model based on the USBR's four proposed dams to assess the implications for Ethiopia, Sudan, and Egypt. The linear model lumps the four dams into one, and determines power solely based on release of water (disregarding head levels). The model runs for an annual cycle, with average hydrologic monthly inputs, optimizing hydroelectric power within Ethiopia.

The Nile Decision Support System, and specifically its Decision Support Tool (DST), as created by the Georgia Water Research Institute, was prepared for the United Nation's Food and Agriculture Organization (FAO) for delivery to all 10 countries within the Nile Basin, but is otherwise proprietary information. It is a software prototype that "models the entire Nile Basin system and assesses the trade-offs and consequences of various cross-sector and basinwide development scenarios," and is intended to be a tool that allows policy makers to craft informed decisions with an understanding of basinwide implications (FAO 2004). Nile DST uses optimization techniques to solve a number of scenarios (e.g., downstream flow requirements, with and without hydropower projects, etc.) based on hydrologic and climatologic data from 1912–1990 (S. Bourne, personal communication, 2005). It attempts to answer queries related to hydropower and irrigation project value, reservoir regulation policies, and flow regulation on wetlands, by using critical criteria, including water supply shortages and withdrawals, reservoir levels, flood and drought severity, and energy generation statistics (Georgakakos 2007).

A final model incorporating the four dams is the Nile Economic Optimization Model (NEOM), coined "the first economic model designed to optimize the water resources of the entire Nile Basin" (Whittington et al. 2005). The model integrates hydrologic and economic information to address water resource allocation not based on the individual country's rights, but on a basinwide scale, and from the perspective of perfect collaboration. The model runs over an annual cycle with monthly inputs, with the user allowed to control the hydrologic level (wet, dry, or average year) as well as withdrawal demands and minimum flow requirements. Streamflow conditions are based on historical climate. The model attempts to answer "economic pressures" related to upstream withdrawal to reduce evaporation, downstream withdrawal to optimize hydropower, upstream storage to reduce evaporation, and withdrawal of water where its user value is highest.

Both Nile DST and NEOM allow for the inclusion of the four proposed dams along the Blue Nile in Ethiopia in any combination. The levels of detail to which the dams are modeled is unknown, but are reported as "sufficient." In choosing to include a dam in the model, the reservoir is assumed instantaneously filled to a design or full level, such that it is immediately operational and/or available for irrigation withdrawals.

While the creation of these models has been a welcome addition to the body of literature on the Nile, more importantly, they have also fostered communication between Nile Basin countries and have given them a tangible assessment tool. Policy makers are theoretically able to make informed water resources decisions, and evaluate the benefits and drawbacks in conjunction with neighboring countries. Unfortunately, the uptake of these models by policy makers and users has been limited for a variety of operational and political reasons. Several critical aspects these models do not incorporate may have serious implications on future investment decisions. These aspects include the transient filling stages of the dams and potential downstream constraints, the staging of when the dams come on-line, and the implications of stochastic modeling of variable climate and climate change. The Investment Model for Planning Ethiopian Nile Development (IMPEND) built for this study has been created to address these issues in an effort to understand the true implications and realistic feasibility of these dams in the 21st century, over a varying set of conditions, and provide users with an operationally based management tool for decision making.

IMPEND Model Framework

IMPEND is a deterministic (perfect foresight) water resources system optimization model, written with the General Algebraic Modeling System software [General Algebraic Modeling System (GAMS) 2005, http://www.gams.com/], requiring a single input file including monthly streamflow and net evaporation at the four Ethiopian Dam locations and at the existing Roseires Dam in southeastern Sudan. The model thus encompasses the Blue Nile River from its inception at Lake Tana to the Roseires Dam, just beyond the Sudan-Ethiopian border. The current version values hydropower at 8 cents per kilowatthour and irrigated crops at $325 per hectare; net present benefits constitute 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 100 years for this analysis, resulting in a time period of 2000–2099. Costs are external and applied through a postprocessor. Specific model equations and details are provided in the Appendix.

One of the most important attributes of IMPEND, which other models to date do not incorporate, is the ability to assess the transient period; most existing models assume the four dams come online simultaneously. Although possible, the staggering of dam construction is a much more plausible alternative. IMPEND is capable of both assessments; for the staggered case, the dams are presupposed to come on-line in 7-year intervals. Benefits for each dam may begin postconstruction of that dam. The reservoirs may be modeled as initially empty, and allowed to fill dependent upon streamflow conditions and downstream requirements. Of course, the reservoirs may also be assumed initially full, for comparison with other models and studies assuming this condition. Another vital characteristic of the model is its ability to be dynamic. The model is driven by monthly inputs, which may vary from year to year, as prescribed by the input file. This allows for scenarios from the historical climate record or potential future climate regimes, including climate change. Analysis from a historical or climatological perspective only, as performed in existing models, may well misjudge long-term project benefits.

IMPEND is also capable of assessment over various interest (or discount) rates, however for the purposes of this paper, this rate has been restricted to 10%. This social rate of discounting has been used by others (Jabbar et al. 2000) and falls within the range of discount rates experienced by Ethiopia within the last 5 years (Central Intelligence Agency 2006). The rate within Ethiopia is highly variable due to the heavy dependence on agriculture coupled with extreme vulnerability to floods and droughts.

Another critical characteristic is the flexibility of downstream flow policies, modulated by the downstream flow constraint established at the entrance to Roseires Dam. The constraint not only prescribes how the proposed Ethiopian reservoirs may be filled (timing and quantity) and the allotment to irrigation, but also allows for the assessment and characterization of potential impacts on downstream countries. The flow constraints considered here may follow one of two policies. The first policy allows for a share of the annual flow (passing the Sudan-Ethiopian border) to be retained within Ethiopia (5% 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 second 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 (henceforth named 5% and 50%, respectively) 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.

IMPEND and Climate Scenario Data Sources

Historical streamflow records were obtained from the National Center for Atmospheric Research's (NCAR) ds552.1 data set (Bodo 2001), including 1912–1990 at Roseires Dam. Hydrologic and climatic data, specifically streamflow and net evaporation, are produced monthly for each dam site by the hydrologic model

WatBal, a simple, lumped parameter, average-monthly global rainfall-runoff model (Yates 1996; Yates and Strzepek 1998) using the CRU TS 2.0 and CRU CL 2.0 data sets the University of East Anglia (Mitchell et al. 2004). Crop water requirements for agricultural irrigation along the Sudan-Ethiopia border are based on CropWat, a software program designed by the United Nations FAO (CropWat; version 4.3 1999). These requirements are dynamic, dependent on concurrent precipitation and temperature. Further dam, reservoir, and power characteristics are provided in the USBR preliminary study (Bureau of Reclamation, U.S. Department of Interior 1964).

Climate scenarios, outlined in the following section, include analyses based on historical data, the ENSO phenomenon, and the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES). The ENSO scenarios incorporate the Niño 3.4 monthly index, obtained from the National Oceanic and Atmospheric Administration's Climate Prediction Center, based on National Centers for Environmental Prediction (NCEP)/NCAR reanalysis data (Kalnay et al. 1996), available from 1950 to the present. Climate data for creation of scenarios based on the IPCC's SRES is garnered from the TYN SC 2.0 data set (0.5° by 0.5° grid for 2001–2100) from the University of East Anglia (Mitchell et al. 2004).

Climate Scenarios

Climate scenarios are created to assess the impacts of climate variability and climate change on the proposed hydropower and irrigation system. The following paragraphs outline the methodological procedure for developing precipitation and temperature time series, which are subsequently transformed into streamflow by the WatBal rainfall-runoff model.

The first scenario employs simply repeating the conditions of the 1961–1990 period, and represents the historical base case. A historical ensemble of streamflow and net evaporation values for each dam site is also created based on 1961–1990 conditions, and represents future scenarios in which no change in climate is expected. To create each new ensemble member, some preprocessing steps are required, including implementation of a *K*-nearest neighbors (*K*-nn) weather generator technique (Rajagopalan and Lall 1999; Yates et al. 2003; Clark et al. 2004). The assumption has been made that each month's weather is dependent upon the previous month's weather, due to persistence in the climatic system, yet not significantly correlated to months of more than one lag. This *K*-nn technique produces monthly variables of precipitation and temperature (i.e., weather) that formulate unique years, yet are statistically identical to the original historical climate record. The procedure starts with randomly choosing a beginning month for the first year (any January) from the actual historical record. The Mahalanobis distance (Davis 1986; Yates et al. 2003) between the first month's precipitation and temperature to all other years of January precipitation and temperature in the historical record (excluding itself) are compared, and the *K* closest months (and corresponding year) are retained. For the historic ensemble, *K* is equal to 5, predetermined by a generalized cross-validation score function (Craven and Wahba 1979). Once the *K* neighbors have been established, they are ordered and one is selected by means of a bootstrap technique with a kernel density estimator that weighs the neighbors. The following month (February) from the year that was selected becomes the next month in the series for the first year. The process is then repeated using February distances to choose March, etc. The January value for any year after the first is simply based on the previous year's December. In this way, actual values are resampled from the historical record, but different yearly combinations of months are produced. The ensemble is statistically indicative of the base case.

ENSO events have been shown to have significant influence in the upper Blue Nile region (Block and Rajagopalan 2007). 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 2005). To evaluate these two diverging paths, two types of climate scenarios are established: one representing a doubling of El Niño events, and the other representing a doubling of La Niña events, as compared to their frequency during 1961–1990. As with the historic approach, ensembles of each ENSO scenario are created. The methodology differs only slightly, with the necessity of weighting El Niño or La Niña years accordingly. For this study, the average of the March–May Niño 3.4 index gives indication of whether the year will be classified as an El Niño, a La Niña, or neither. The Niño 3.4 values are appended to the 1961–1990 historical record, and a new record is derived by placing weights on the El Niño (or La Niña) years and bootstrapping, producing two ensembles in which ENSO years occur approximately twice as often.

The SRES established a variety of forecasts under scenarios based on hypothetical climate change. These scenarios were created in the late 1990s, and have been used extensively in global circulation models (GCMs) to predict future global conditions, specifically for 2001–2100. For this study, the results from five GCMs under two different scenarios, from the A2 and B2 storylines, are considered (Nakicenovic et al. 2000). The five GCMs, all used in IPCC assessments, include the Canadian Centre for Climate Modeling and Analysis' Coupled Global Climate Model (CGCM2), the Commonwealth Scientific and Industrial Research Organization's Mark 2b Climate Model (CSIRO mk2), the Department of Energy's Parallel Climate Model (DOE PCM), the Hadley Centre's Coupled Atmosphere—Ocean Model (HadCM3), and the Max-Planck-Institute's Model (ECHam4).

The time series of projected July streamflow from the hydrological model for the first five decades of the 21st century for the greatest increase (B2 from ECHam4), largest decrease (A2 from CGCM2), and the median case (B2 from DOE PCM), are illustrated in Fig. 3. Each time series is relative to the 1961–1990 base at the Karadobi Dam, approximately 385 km downstream from Lake Tana. Only these three SRES scenarios are fully considered in this study. The increasing or decreasing trends are assumed to be smooth, and are fit accordingly. The trends are also dam site specific, but generally follow the same pattern. To add variability to the SRES projections, the variability from the historical base case was used. This was accomplished by removing the 1961–1990 trend and adding the residuals to the SRES projected trend for each month.

Results and Discussion

Two critical modeling features are emphasized and evaluated in this work: the importance of including the transient stage and the influence of climate variability and climate change on project development.

Transient versus Nontransient Scenario Results

To demonstrate the effects of including versus ignoring the transient stage, construction staggering, and downstream flow policies

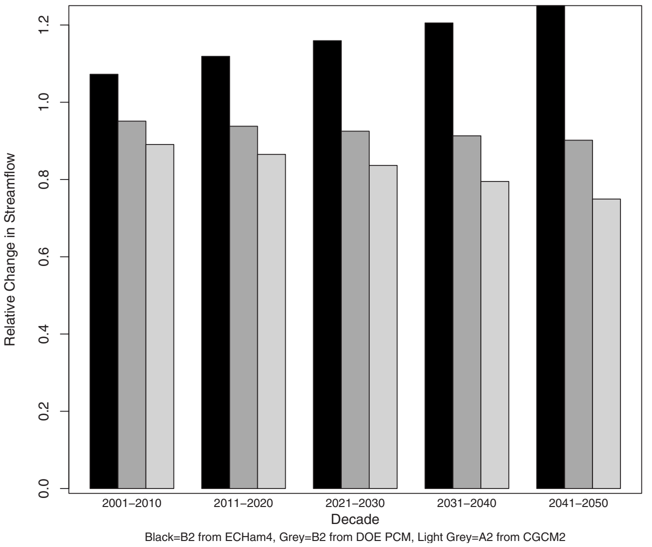

Fig. 3. Bar plots of July streamflow projections at Karadobi Dam for the first five decades of the 21st century for three selected GCM scenarios

Table 1. Financial and Downstream Flow Effects of Including the Transient Stage, Construction Staggering, and 50% Downstream Flow Policies in the IMPEND b-c Analysis

	Financial		Flow	
			Average annual decrease	
Scenario	b-c ratio	Net benefits (10^6 US\$)	%	10^9 m^3
No stagger: full reservoir	2.19	9,160	3.5	1.6
Stagger: empty reservoir	1.68	2,760	6.0	2.7
Difference		6,400		1.1

Note: Interest rate=10%; no stagger=all dams built in the first 7 years; stagger=dams built sequentially in 7-year increments; full or empty reservoir=initial level of reservoir; and difference=difference between the no stagger-full policy and the stagger-empty policy.

in a benefit-cost (b-c) analysis on the upper Blue Nile Basin, IMPEND is run for 100 years, based on 1961–1990 monthly climatic values at an interest rate of 10%. Two transient scenarios are examined: (1) no stagger (dams are built simultaneously over a 7-year period) with reservoirs initially full and (2) stagger (dams built sequentially in 7-year increments) with reservoirs initially empty. The first scenario describes the situation in which all dams are immediately on-line and producing hydropower by ignoring the transient stage. The second scenario describes a more realistic approach, staggering construction due to financial constraints, and accounting for the filling stages of each reservoir. These conditions are independently evaluated under the 50% flow policy. Fig. 4 depicts annual discounted costs, benefits, and net benefits from the two transient scenarios under the 50% flow policy. The dissimilarities are clearly evident. Even bearing all costs early in the project, the first transient scenario benefits immediately by having the reservoirs initially full. Table 1 illustrates the financial repercussions of considering these conditions to Ethiopia. Not unexpectedly, the no stagger-full reservoir condition (first) produces larger estimates of b-c ratios and net benefits in comparison to the stagger-empty reservoir condition (second). The difference in net benefits between the two transient scenarios is in excess of \$6 billion, approximately the undiscounted cost of three proposed dams.

Downstream flow losses under these conditions are also presented in Table 1, and are critically important for both Ethiopian and downstream country planning. The second transient scenario (stagger-empty reservoirs) impounds over 170% more water annually, on average during the first 30 years, predominantly to fill the reservoirs, in comparison to the first scenario (no stagger-full reservoirs). This equates to approximately 1.1 billion–1.4 billion m^3 of additional water each year during the same period.

Isolating the transient filling aspect alone under the no stagger policy also proves illuminating. Although the simultaneous construction of all dams and the irrigation infrastructure over 7 years is quite unlikely, it is telling of the importance of modeling the transient stage. Fig. 5 reflects reservoir storage for initially full

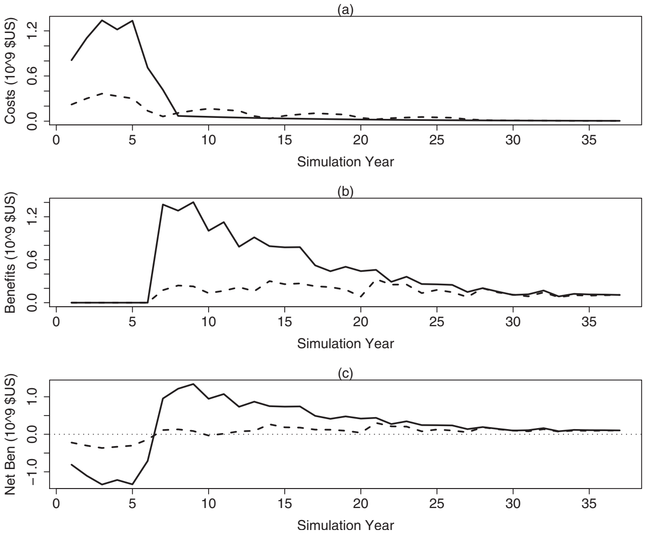

Fig. 4. Annual discounted (a) costs; (b) benefits; and (c) net benefits for the no stagger—full reservoir (solid line) and stagger—empty reservoir (dashed line) scenarios under the 50% flow policy

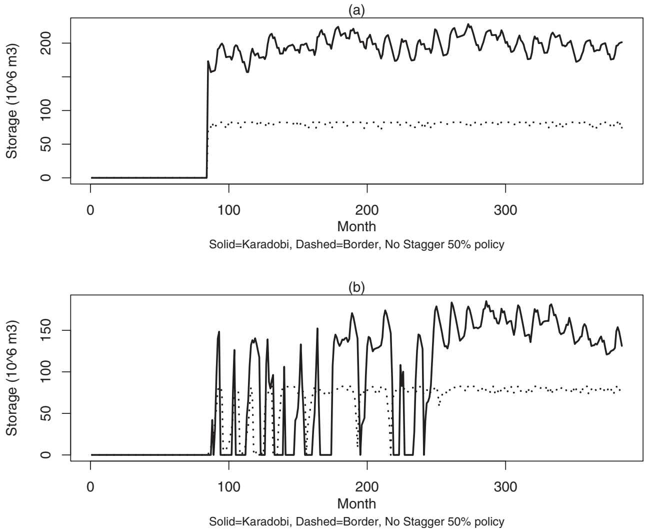

Fig. 5. Individual monthly reservoir filling patterns under the “no-stagger” 50% flow policy cases for (a) initially full; (b) initially empty reservoirs, for the first 32 years

Table 2. b-c Ratio Ranges for Historical and ENSO Ensembles, and for Three SRES Scenarios, under the 5 and 50% Flow Policies

Flow policy (%)	Scenario					
	Historic	2×La Niña	2×El Niño	B2, ECHam4	B2, DOE PCM	A2, CGCM2
5	1.48–1.72	1.49–1.76	1.43–1.66	1.80	1.64	1.39
50	1.18–1.82	1.41–1.91	1.07–1.63	1.75	1.42	1.07

Note: The interest rate is 10%.

and initially empty reservoirs under the 50% downstream flow policy (Karadobi and Border Dams only). It is not until 13 or more years after impoundment begins that reservoir levels end their period of wild fluctuations for the initially empty state, necessary to generate hydropower in the crucial early years. Only after this time, when both the initially full and initially empty states have relatively similar total quantities of water in their systems, would optimal reservoir operations be expected to produce similar reservoir level patterns. While it may be blatantly clear that initially full reservoirs are an impossibility, failure to account for their filling in the planning stages results in a grossly flawed economic analysis.

Historical and Climate Change Scenario Results

To confine the analysis, the number of scenarios for this portion of the study was selectively pared down with the intention of adequately scoping a relevant range of possibilities that could inform policy, planning, and decision making. Only the 5 and 50% flow policies and 10% interest rate, as previously discussed, are considered. Construction staging is limited to dams coming on-line in 7-year increments and irrigation infrastructure built over a 3-year period. Reservoirs are all initially empty, as previously rationalized.

Table 2 presents b-c ratio ranges for the historical and two ENSO ensembles, as well as for the three SRES scenarios. The b-c ratios for a doubling of La Niña are approximately equivalent to those of the historic ensemble for the 5% policy, but slightly improved for the 50% 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 generally conditions, resulting in less opportunity for water-related benefits. This is especially apparent in the 50% flow policy scenario in which some El Niño ensemble members plummet to a b-c ratio just above 1.0. This depressed level 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 this specific development project may be called into question. In actuality, the b-c ratios for the doubling of El Niño may well be an overestimation, as the likelihood of sustaining perfect reservoir management is miniscule.

Figs. 6(a and b) illustrate the probability-density functions (PDFs) of net present value for all three ensembles under the two flow policies. As reflected in Table 2, the El Niño PDFs are noticeably lower than the historical PDFs, and the La Niña PDFs are approximately equal to the historical PDFs. Figs. 7(a and b) demonstrate annual benefit and cost curves for the median of each ensemble. Again, as expected, the El Niño benefit curve is lower than the other two benefit curves for much of the period displayed. Energy production results illustrate comparable findings to Fig. 6. Using an industrial growth rate of 6% (Central Intelligence Agency 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.

Not all members of the El Niño ensemble produce feasible results in IMPEND under the 50% flow policy. These results have been eliminated from the previous analysis, biasing the El Niño PDF toward larger net present values. It is paramount,

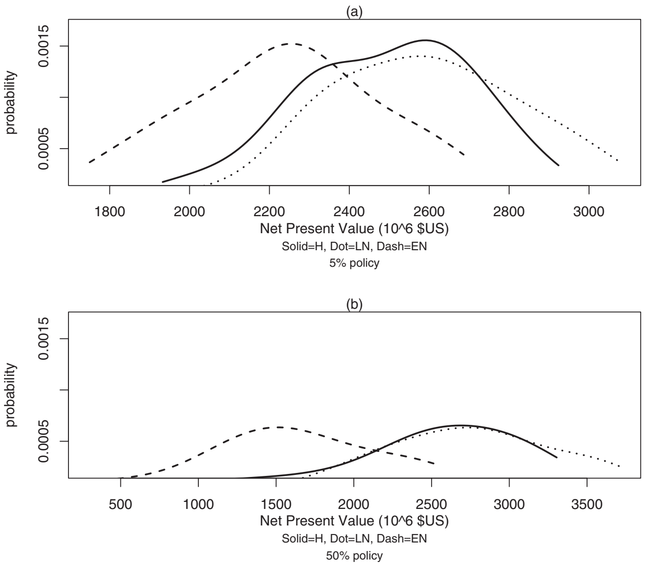

Fig. 6. PDFs of net present value for the historic (H), La Niña (LN), and El Niño (EN) ensembles under the (a) 5; (b) 50% flow policies

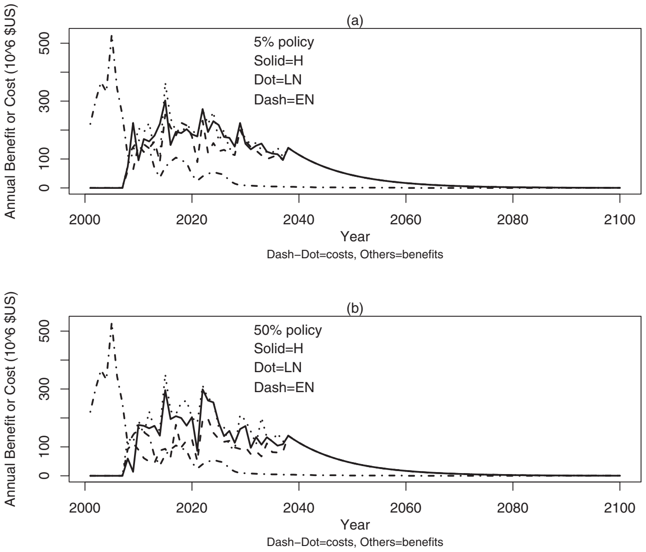

Fig. 7. Annual benefit and cost curves for the historic (H), La Niña (LN), and El Niño (EN) ensembles under the (a) 5; (b) 50% flow policies

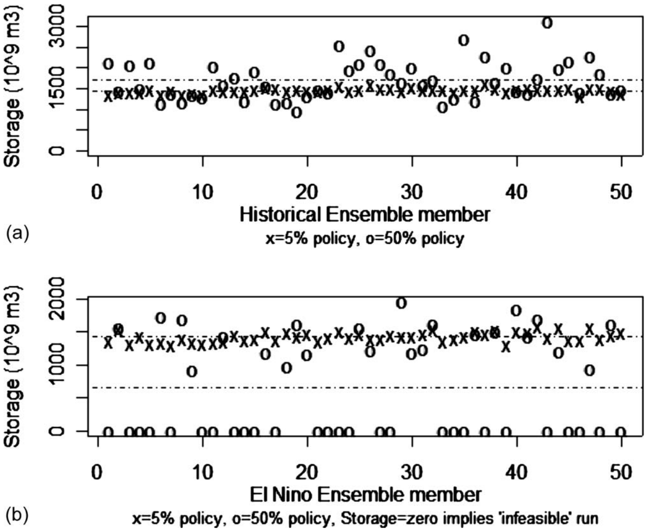

Fig. 8. Cumulative storage for the first 10 years of each (a) historical; (b) El Niño ensemble member for the 5 and 50% flow policies. The dashed lines represent ensemble means.

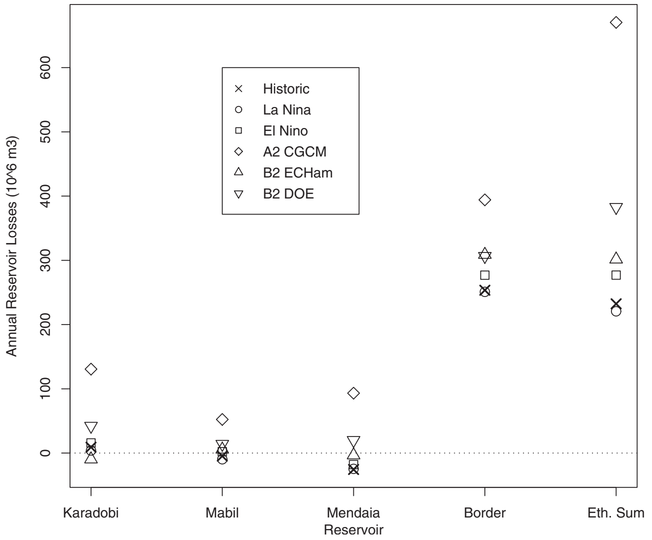

Fig. 9. Expected net evaporation rates for individual reservoirs and the cumulative sum

however, to realize that the prospects of infeasibilities are real, due to early or successive dry years, when no water may be impounded, yet large evaporative demands and minimum downstream requirements must still be met. Infeasibilities occur when any of these constraints are not satisfied; in operational terms, this would imply a reduction in downstream flows below established requirements, possibly resulting in financial penalties or similar. Fig. 8 illustrates cumulative storage for the first 10 years of each historical and El Niño ensemble member for the 5 and 50% flow policies. The dashed lines represent ensemble means. Any storage equal to zero implies an infeasible run. The 5% flow policy storage results are quite tightly grouped, as expected, due to the annual assurance of water. For the 50% flow policy, no infeasibilities are generated in the historical ensemble; just over one-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 50th percentile. Clearly, 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 may play a major role in determining the success or failure of the proposed projects. Overall, the 5% flow policy appears to be more robust to modeled climate changes than the 50% flow policy, as it consistently outperforms the 50% flow policy in drier conditions, and is nearly on par with it in wetter conditions.

Evaporation Demands and Potential Savings

Due to its equatorial positioning, the Nile River has high rates of evaporation in its channels and reservoirs, and evapotranspiration in irrigation systems. It is estimated that at least 10 billion m^3 alone are lost annually from Lake Nasser, the reservoir behind the Aswan high dam in Egypt (Murakami 1995). Storage in the Ethiopian highlands could potentially conserve vast amounts of water as compared to storage in Lake Nasser, due to minimization of open water evaporation. The four Ethiopian reservoirs, while only collectively able to store approximately 50% of Lake Nasser's potential, would typically lose less than 0.25 billion m^3 in net evaporation (evaporation less precipitation) in an average year under historical conditions. Fig. 9 displays expected net evaporation rates for individual reservoirs and the cumulative sum. Lower overall temperatures, higher rates of precipitation, and a considerable difference in impounded surface areas (approximately one-quarter) between the Ethiopian and Egyptian reservoirs all contribute toward potential savings. Among the Ethiopian projects, the reservoir behind Border Dam clearly contributes the majority of losses, due primarily to its proximity to the arid region.

Climate change scenarios indicated an even greater absolute difference. Strzepek et al. (1996) reported that a loss of 14 billion–15 billion m^3 from Lake Nasser may be expected under a scenario in which atmospheric levels of carbon dioxide are doubled, corresponding to a nearly 50% increase in net evaporation over current conditions. Of the climate change scenarios considered in this study, the SRES B2 scenarios represent a similar carbon dioxide level, providing a relatively fair comparison; the A2 scenario corresponds to approximately 2.5 times current levels. From Fig. 9, percent changes in expected net evaporation of the B2 scenarios over historical conditions are on the order of those in the Strzepek et al. (1996) study. Absolute differences, however, are markedly different; additional losses in Ethiopia are likely to be less than 150 million m^3, compared to 4 billion–5 billion m^3 from Lake Nasser. Even the A2 scenario, in which net evaporation rates nearly triple over historical rates, only represents additional losses of approximately 400 million m^3 per year. Conserving even a portion of this could greatly benefit both Ethiopia and Egypt.

Summary and Conclusions

The IMPEND modeling framework is presented to address critical features of international basin water resources system modeling often ignored or dismissed, including the transient stages of large-scale reservoirs, relevant flow retention policies and associated downstream consequences, construction staging, and the implications of stochastic modeling of variable climate. The effects of including or ignoring the filling and construction stagger features on the Blue Nile in Ethiopia are demonstrated with IMPEND on a 100-year simulation, using 1961–1990 monthly climatic values at an interest rate of 10% and a fixed 7-year stagger period between dams coming on-line. Model results disregarding these aspects demonstrate overestimations of $6 billion in benefits and 170% in downstream flows compared to model results accounting for them. Ignoring these aspects clearly represents a flawed economic analysis, and may result in errant planning and decision making for both Ethiopia and downstream countries. For the development projects specified, the b-c ratios for models including transient conditions and climate variability are found to range from 1.2–1.8 under historical climate regimes. Climate change scenarios, represented either by changes in the frequency of El Niño and La Niña events or by SRES projections, indicate potential for small b-c ratio 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 b-c ratios as low as 1.0, with numerous runs producing potentially infeasible hydropower/irrigation projects due to a lack of timely water. In terms of evaporative savings, storage in the Ethiopian highlands could potentially conserve vast amounts of water as compared to storage in Lake Nasser.

Climate variability and climate change influences on this system are clearly worthy of consideration and should be an integral part of large-scale design and development within Ethiopia. The policy implications of these findings are numerous. First, the need to undertake significant economic planning and the necessity of securing energy trade contracts with neighboring countries prior to extensive expansion will be critical. Second, 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 (Nile Basin Initiative 1999). Regardless of the final structure of any contract between these countries, a key feature must include its ability to be flexible and adaptable to future climatic conditions without being overly ambiguous risking limited development. Finally, a redesign of the system considering climate change may produce improvements over realizations based on historical data only. If the climate tends toward wetter conditions, as prescribed in the IPCC projections (Giannini et al. 2008), additional streamflow could be allocated for hydropower or irrigation.

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 assessing a smaller time window, without the benefit of perfect foresight. This may be accomplished by solving the model yearly with the expectation that the following year would produce average climatic conditions. In a separate variation, a precipitation forecast model (Block and Rajagopalan 2007) 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 climatic conditions and a *K*-nn weather generator reflecting potential near-term changes. All approaches would likely reduce project performance and ensuing b-c ratios.

The inclusion of supply and demand curves into IMPEND, both for hydropower and agriculture, would also prove valuable, allowing for a quantitative analysis of trade-offs between sectors. Dynamic curves could reflect pricing and availability, which would undoubtedly change throughout the project life. The curves could also play a key role in the assessment of varying climatic conditions, as marginal prices may be noticeably different between scenarios.

Finally, additional scenarios to those proposed may be considered, including optimal stagger and Lake Nasser peak filling. The first involves modifying IMPEND to determine a relevant range of years for optimal staggering between dam construction, or perhaps deciding if construction of all dams is necessarily most advantageous, especially under potential climate change conditions. The second scenario entails allowing Lake Nasser to completely fill in a designated year, without wasting water through intentional spilling, and impounding most of the next year's streamflow behind a recently constructed dam in Ethiopia, yet permitting enough to pass to meet Sudan's needs. Upon completion of the subsequent dam, the process could be repeated, allowing for immediate filling and benefits. Undeniably, this scenario would require unprecedented cooperation and trust among the collaborating countries.

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Appendix

The objective function for IMPEND consists of maximizing net benefits

$$\mathrm{OBJ} = \max \sum_{y} \sum_{s} (\mathrm{NB}^{I}_{y,s} + \mathrm{NB}^{\mathrm{HP}}_{y,s}) \tag{1}$$

where y=year; s=dam/reservoir site (Karadobi, Mabil, Mendaia, and Border); and B=benefit (I=irrigation, HP=hydropower).

The individual net benefit components are further described in Eqs. (2)–(5)

$$\mathrm{NB}^{I}_{y,s} = \sum_{y} \sum_{s} (Q^{I}_{y,s}/\mathrm{CWR}_{y,s}) \times P^{I} \times D \tag{2}$$

$$B^{\mathrm{HP}}_{y,s} = \sum_{y} \sum_{s} (E_{y,s}) \times P^{\mathrm{HP}} \times D + \sum_{y} \left(\min \sum_{s} E_{s,m*} \right) \times P^{\mathrm{CB}} \times D \tag{3}$$

where Q^{I}=flow diverted from reservoir s for irrigation (m^3/month); CWR=crop water requirements per hectare (m/

year); CB = capacity benefit (will be described later herein); P = price (for I = irrigated crop, HP = kW·h, CB = kW·h) (U.S. dollars); D = discount rate; E = energy generated from hydropower (gigawatthour/month); m^* = months in corresponding year (i.e., for year 3, m^* = 25–36); and

$$Q_{y,s}^I = \sum_{m^*} Q_{m,s}^I \tag{4}$$

$$E_{y,s} = \sum_{m^*} E_{m,s} \tag{5}$$

where m = month (1–1,200 for a 100-year simulation).

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. Eqs. (6) and (7) present the monthly reservoir storage balance and monthly energy production equations, respectively

$$S_{s,m+1} = S_{s,m} + Q_{s,m}^{\mathrm{RO}} + Q_{s,m}^{\mathrm{US}} - \mathrm{NE}_{s,m} \times \mathrm{RA}_{s,m} - \beta_s \times \mathrm{CE}_{s,m} - Q_{s,m}^P - Q_{s,m}^{\mathrm{SP}} - Q_{s,m}^I \tag{6}$$

$$E_{s,m} \leqslant Q_{s,m}^P \times H_{s,m} \times e_{s,m} \times \alpha \tag{7}$$

where S = reservoir storage (m^3); Q^{RO} = inflow to reservoir from basin runoff (m^3/month; Q^{US} = inflow to reservoir from upstream = $Q^P + Q^{\mathrm{SP}}$ of u/s dam, m^3/month; NE = net evaporation (potential evapotranspiration minus effective precipitation) (m^3/month); RA = reservoir area (m^2); B = channel properties factor; CE = channel evaporation (m^3/month); Q^P = flow for power, released through turbines (m^3/month); Q^{SP} = flow over the spillway (m^3/month); e = turbine and generator efficiency; and α = conversion factor.

Rated (or installed) power, according to the USBR preliminary report, is assumed to be at design head, and increases linearly to the ultimate head (Bureau of Reclamation 1976). The head level must be at the minimum operating level before power generation may commence.

Constraints are included to regulate monthly outlets from Border Dam based on a percentage of the annual flow. The maximum streamflow exiting Border Dam in any month is 1/9 the annual total, and the minimum streamflow is 1/36 the annual total, as outlined in Eqs. (8) and (9). The fractions are loosely derived from assessment of streamflow on the Colorado River at Hoover Dam (Dreamflows 2006, www.dreamflows.com). The constraint illustrating allowable annual flow based on the flow policy is presented in Eq. (10)

$$Q_m^R \geqslant \frac{1}{36}(Q_m^{\mathrm{RO},R} + Q_m^{\mathrm{US},R} - \beta_R \times \mathrm{CE}_m^R) \tag{8}$$

$$Q_m^R \leqslant \frac{1}{9}(Q_m^{\mathrm{RO},R} + Q_m^{\mathrm{US},R} - \beta_R \times \mathrm{CE}_m^R) \tag{9}$$

$$Q_y^R \geqslant \sum_s \sum_{m^*} (Q_{m,s}^{\mathrm{IN}}) \times (1 - \mathrm{FP}) \tag{10}$$

where R = Roseires; Q^R = flow at Roseires (furthest point modeled downstream); $Q^{\mathrm{RO},R}$ = inflow to Roseires from basin runoff; $Q^{\mathrm{US},R}$ = inflow to Roseires from Border power and spill releases; CE^R = channel evaporation between Border and Roseires; and FP = flow policy (fraction retained in Ethiopia).

The model is also encouraged to minimize the number of low streamflow months from Border by the addition of a capacity benefit. Essentially, the energy from the lowest energy-producing month each year is rewarded through a capacity benefit by receiving 24 cents/kW·h as opposed to the standard 8 cents/kW·h (K. Strzepek, personal communication, 2006). This also works to reduce the number of high flow months, and creates a more balanced distribution.

Net evaporation from the free water surface is computed monthly for the four reservoirs and channel lengths in-between. The value is multiplied by the dynamic reservoir area to determine losses or gains. For computation of net channel evaporation, which is comparably quite small, channel lengths and widths are assumed constant.

The benefits of water for irrigation are configured differently than in other simulation models by employing a simple regression model between the annual crop water requirements and the annual net evaporation. The ensuing linear relationship is embedded in IMPEND such that crop water requirements are dynamic on a year to year basis, and roughly reflect the requirements based on current conditions. This is a marked improvement over using an annual average, and becomes especially critical in dry years.

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