Does Climate Matter? Evaluating the Effects of Climate Change on Future Ethiopian Hydropower

Paul Block, Casey Brown

Abstract

This research aims at quantifying the effect and importance of considering future climate change on large-scale infrastructure in a developing country context. Plans are underway for major hydropower development in Ethiopia, a water resources-rich nation, yet consideration of climate change on design, operation, and eventual benefits of the system remains uncharted. If current strategies are reliant on stationary climate, what future climatic conditions could warrant measurable design changes or even project abandonment? How much do long-term benefits change, and is this level significant, especially considering economic variability, policy, and other competing demands? A vacuum currently exists for decisionmakers; there is clear recognition that climate change information ought to be considered but little experience in incorporating the seemingly complex science into design and operational decisions. This research aims to establish and demonstrate an approach for integrating climate change information into project evaluation, ultimately creating a serviceable format from which scientists outside of the climate specialty may address climate risk management decisions. To model the system, potential future precipitation and temperature trends are utilized to drive a coupled hydrology–Ethiopian hydropower optimization model, producing project benefit-cost ratios over 50 years. These results are subsequently evaluated through benefit-cost ratio surface illustrations for varying economic, policy, and project scope conditions. Preliminary results suggest nonstationary climate influences may warrant economic attention in comparison with traditionally dominant factors. Additionally, drier than historically normal conditions appear to have a greater detrimental effect on overall benefit-cost ratios than positive effects expected under wetter than normal conditions, a constructive conclusion for early project planning and design.

Keywords: climate, climate change, decisionmaking, water resources, hydropower, risk management, Ethiopia

Introduction

Weather and climate are inherently uncertain, rendering appropriate water resources planning and management anything but deterministic. Seasonal to interannual forecasts attempt to characterize and reduce operational and design uncertainty, but as the forecast or projection horizon is extended, uncertainty invariably grows (Enfield and Cid-Serrano 2006). Given the extraordinary attention that climate change has received recently, few water resources managers (or public citizens) remain unaware. There is clear recognition that climate change information ought to be considered, but little experience with how to incorporate the seemingly complex science into design and operational decisions. This vacuum gives rise to the question of how to assess existing or future projects given the current level of climate change knowledge and uncertainty. Is climate change indeed significant and influential enough to warrant a fully inclusive analysis, or is designing according to classical principals and methodologies still suitable? How does one decide, especially given associated changes in population, economics, policies, and preferences (James et. al 1969)? If climate change does appear to be sufficiently influential, how can the associated impacts be incorporated into operations or design? Significant research activity has focused on appropriate water resources assessment and adaptation strategies in relation to climate change uncertainties (Carter et. al 1994, Rogers 1997, Frederick 1998, Fankhauser et. al

Block is an associate research scientist, International Research Institute for Climate and Society (IRI), Columbia University, Palisades, NY 10964. Brown is an assistant professor of civil and environmental engineering, University of Massachusetts, Amherst, MA 01003. Email: pblock@iri.columbia.edu; cbrown@ecs.umass.edu.

1999, Adger et. al 2003). This study builds on that work and begins to address these critical questions, proposing one approach in the context of hydropower design within Ethiopia for 2001–2050. While it is clear that the spatial variability of climate change projections requires a unique analysis for each project in each geographical region, it is anticipated that the methodology and assessment tools proposed here would be fully transferable.

Application Site

In 1964, the United States Bureau of Reclamation (USBR), upon invitation by the Ethiopian government, performed a thorough investigation and study of the hydrology of the upper Blue Nile basin, coincident with 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 1. 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 2006).

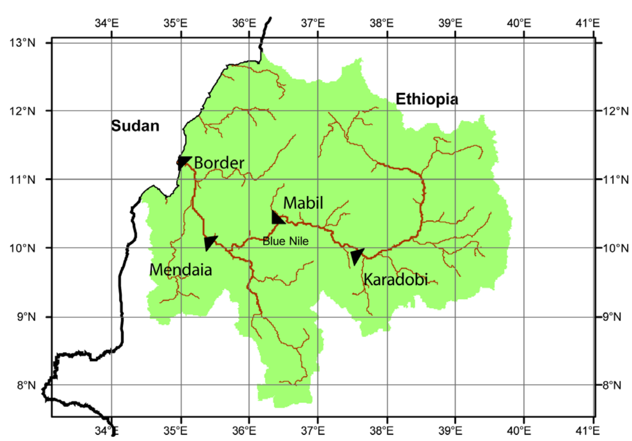

Figure 1. Plan view of proposed hydroelectric dams along the Blue Nile River, as proposed by the United States Bureau of Reclamation.

To this point in time, no dam designs have moved beyond the feasibility stage for a variety of political and financial reasons. Models and evaluations in this study incorporate proposed plans only, limiting the analysis to two or three dams.

Methodology

To address potential climate change influences on the proposed Ethiopian hydroelectric dams, several models and algorithms are necessary, coupled in an iterative fashion, as illustrated in Figure 2.

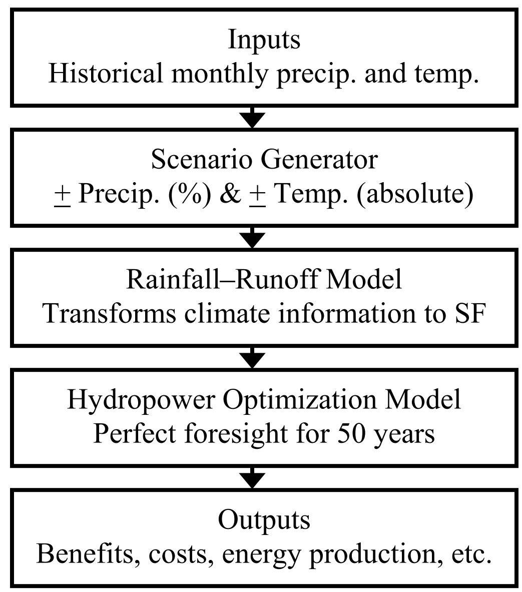

Figure 2. Coupled models required for climate change analysis on proposed Ethiopian hydroelectric dams. SF, streamflow.

The overall structure is not dissimilar from customary static approaches to project/operational design and evaluation. The process is driven with (traditionally historic) climate data then optionally forced through a scenario generator if multiple or trend-added projections are desired. For future nonstationary climate scenarios, the generator imposes prescribed precipitation (e.g. +10 percent) and temperature (e.g. +1°C) changes on top of the actual historic climate data. The synthetic climate scenarios are subsequently imposed on a rainfall-runoff model to produce streamflow (SF) values and evapotranspiration at reservoir inflow points, which in turn drive the hydropower model. Final outputs include project benefits, costs, energy production, reservoir levels, etc.

For the specific projects considered here, the historical monthly climate data were extracted from the University of East Anglia Climate Research Unit's datasets for 1951–2000 (New et al. 1999, Mitchell et al. 2004). Analysis of climate change influences are evaluated monthly over 2001–2050 with varying combinations of potential precipitation (+20, +10, 0, -10, and -20 percent) and temperature (+1°C, +2°C, +3°C) changes for a total of 15 scenarios. Changes are applied in a linear gradient manner; using the temperature (+1°C) and precipitation (0 percent) example, temperature changes in 2001 are essentially equivalent to 1951, but are one full degree higher in 2050 than the historical 2000 value.

The 0.5° x 0.5° gridded rainfall-runoff model CLIRUN2, a derivative of the WatBal model (Yates 1996; Strzepek, 2007, personal commun.), is employed here. CLIRUN2 is a lumped basin, two-bucket model running on monthly time steps, calibrated to historical streamflow at Roseires, Sudan, as available from the National Center for Atmospheric Research (Bodo 2001).

The hydropower model IMPEND (Block and Strzepek, in press) is utilized to model climate influences on potential hydroelectric dams along the Blue Nile River between its inception at Lake Tana, Ethiopia, and Roseires, Sudan, just beyond the Sudan-Ethiopia border. IMPEND is a perfect foresight water resources system optimization model in which dams are constructed and brought online in predefined stages (every seven years in this study). IMPEND is also sufficiently flexible to address both policy and economic influences, especially relevant here for comparison with climate change impacts. Policy influences are characterized by the quantity of streamflow that may be impounded because of anticipated regulations by downstream countries. This is especially critical in the early reservoir filling stages. Total reservoir impoundment is limited here to either 5 or 10 percent of the annual total. Economic influences are portrayed through varying discount rates, static throughout the 50-yr simulation, of 5, 10, or 15 percent.

Although many output variables are of interest for additional analysis, only benefits (B) and costs (C) will be discussed further. Both represent totals over the 50-yr simulation period, discounted back to 2000 US dollars and typically presented as a ratio (B/C ratio).

Results and Discussion

Table 1 presents B/C ratios for development and operation of two dams for 2001–2050, including base (actual 1951–2000 values) and potential climate change conditions, for varying flow policies and discount rates. As anticipated, increases in temperature and declines in precipitation result in lower overall B/C ratios, likewise with rising discount rates and smaller flow policies. The perfect foresight aspect of the hydropower model contributes to the relatively linear trends between scenarios and also represents the highest (unrealistically) attainable B/C ratio. Clearly, under the assumptions established here, if discount rates are at or above 15 percent, the project is unlikely to reach a break-even point. Another point of interest is that temperature increases have little to no effect. This may be predominantly explained away by minimal reservoir surface area (water simply backs up in the channel as opposed to spreading out laterally) and the restrictive flow policies.

To further address the question of whether or not climate change is sufficiently influential on this project and thus warrants a more detailed analysis, Table 1 may be cast into illustrations of B/C ratio surfaces for interpretive purposes. Figure 3 demonstrates the ensuing surface for a flow policy equal to 5 percent and discount rate of 10 percent.

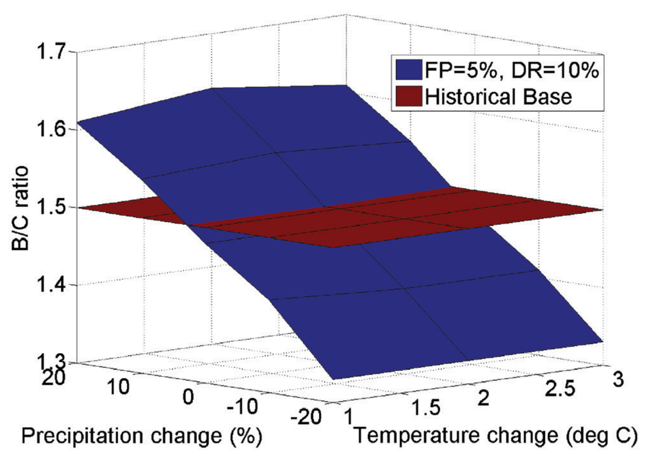

Figure 3. Surface plot of B/C ratios for varying precipitation and temperature changes under a flow policy (FP) of 5 percent and discount rate (DR) of 10 percent (blue). Historical base illustrated as a surface for comparison (red).

For comparison, the base case, also discounted at a 10 percent rate, but assuming no changes in climate, has been displayed as a surface (although it is in actuality a point).

Table 1. Benefit-cost ratios for development of two dams for 2001–2050 discounted to 2000 US dollars.

	Flow Policy = 5%			Flow Policy = 10%		
T, P scenario	**DR=5%**	**DR=10%**	**DR=15%**	**DR=5%**	**DR=10%**	**DR=15%**
historical base	3.12	1.50	0.81	3.51	1.61	0.97
1°, +20%	3.51	1.61	0.86	3.88	1.87	1.02
1°, +10%	3.33	1.55	0.84	3.70	1.81	1.00
1°, 0%	3.12	1.48	0.81	3.47	1.73	0.97
1°, -10%	2.93	1.42	0.79	3.29	1.67	0.94
1°, -20%	2.70	1.33	0.75	3.05	1.58	0.90
2°, +20%	3.55	1.63	0.87	3.92	1.89	1.03
2°, +10%	3.35	1.56	0.84	3.72	1.81	0.99
2°, 0%	3.14	1.48	0.81	3.50	1.74	0.96
2°, -10%	2.92	1.41	0.78	3.28	1.67	0.93
2°, -20%	2.70	1.33	0.75	3.05	1.58	0.90
3°, +20%	3.53	1.61	0.88	3.92	1.89	1.03
3°, +10%	3.32	1.55	0.84	3.71	1.81	1.00
3°, 0%	3.11	1.47	0.81	3.48	1.73	0.97
3°, -10%	2.89	1.41	0.78	3.25	1.65	0.93
3°, -20%	2.67	1.33	0.75	3.03	1.57	0.90

T = temperature, P = precipitation, DR = discount rate

Clearly, as precipitation changes between scenarios, the B/C ratios follow suit. To what degree they change may potentially be critical for planning or redesign purposes. For example, equivalent positive and negative changes in precipitation do not necessarily produce identical changes in the B/C ratio. Given this scenario, if precipitation increases, B/C ratios may elevate by as much as 0.1; having a sense of this a priori is obviously beneficial. Equally important, however, is caution in considering drier conditions for which the B/C ratio may decline by nearly 0.2. Given the economic value of a B/C ratio change (0.2 equates to approximately $550 million US for this example), decisionmakers may be better informed as to whether this constitutes sufficient grounds for further climate change analysis as it pertains to the project.

Project feasibility may also be preliminarily assessed in similar fashion. Figure 4 presents the B/C ratio surface for a flow policy equal to 10 percent and discount rate of 15 percent. A planar surface for a B/C ratio equal to one is also displayed to represent the project break-even point.

Although relatively simplistic at this stage, ignoring external feedbacks which may ultimately boost the overall project returns, and also applying a perfect foresight approach that likely overestimates returns, the surface still serves as a first-order project turning point for decisionmaking. Clearly, only in wetter conditions does the project appear to be viable, and then only minimally, whereas for historically normal and drier conditions, the risk of lower returns increases.

Sensitivity analyses of policies and economic metrics are also possible through this illustrative approach. Figures 5 and 6 compare across discount rates and flow policies, respectively, for varying climate change conditions.

Figure 5 shows a clear distinction between discount rates and the effects of doubling or tripling them. More interestingly, however, is comparing the general slopes of the surfaces. An interpretation of the 15 percent discount rate may be that no additional climate change analysis is necessary, as the surface has little slope and appears relatively uninfluenced. Alternatively, the 5 percent discount rate surface portrays a relatively steeper surface crossing a larger range of B/C ratios, so a more thorough climate change analysis may be justified.

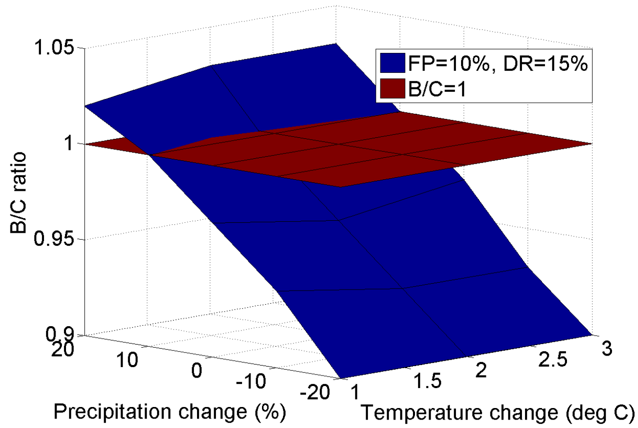

Figure 4. Surface plot of B/C ratios under a flow policy (FP) of 10 percent and discount rate (DR) of 15 percent (blue). B/C ratio equal to 1 illustrated for comparison (red).

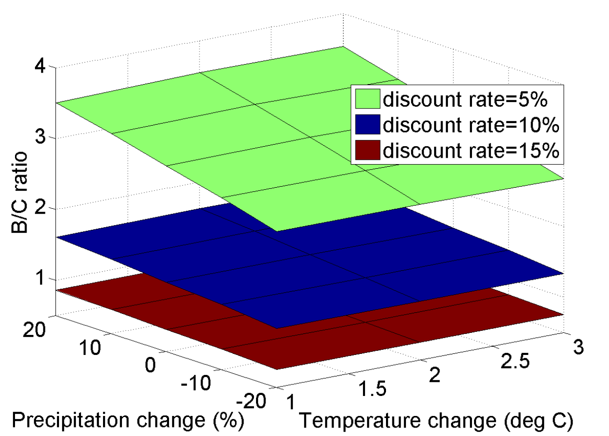

Figure 5. Surface plots of varying discount rates for the 5 percent flow policy.

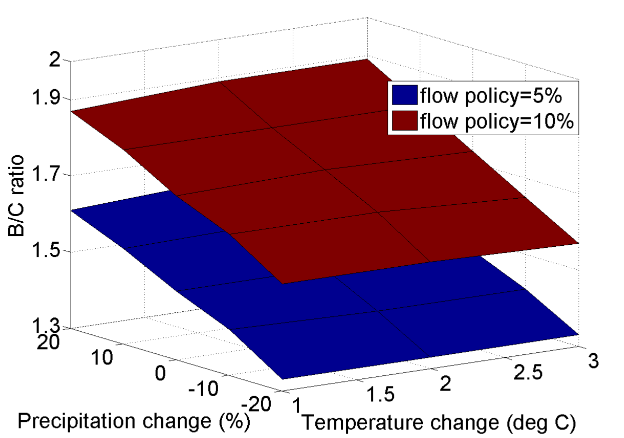

Figure 6. Surface plots of varying flow policies for a 10 percent discount rate.

A plausible interpretation of Figure 6 as related to the necessity of further climate change analysis may be that although both policies appear to be relatively equally affected to changes (similar slopes), the 10 percent policy B/C ratio under the driest conditions is still nearly on par with the best expected B/C ratio under the 5 percent policy. Obviously externalities (e.g. remuneration to downstream countries) become increasingly important and ultimately need to be factored in, but simply understanding the plausible outcomes over a range of conditions may be exceptionally informative.

Comparing B/C ratio surfaces is also revealing for evaluating competing projects under similar conditions. Figure 7 illustrates projects for development and operation of both two and three dams under a 10 percent flow policy and a 5 percent discount rate.

The two projects perform similarly across varying climatic conditions; however, from a B/C ratio perspective, it may be advantageous to select the two-dam option under drier conditions and the three-dam option under wetter conditions.

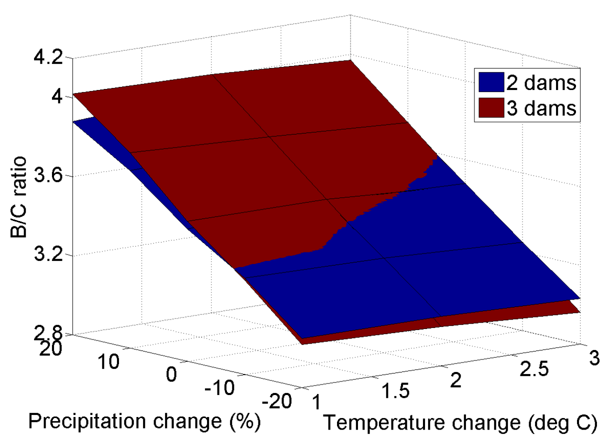

Figure 7. Surface plots for development and operation of two and three dams under a flow policy of 10 percent and discount rate of 5 percent.

Conclusions

This research aims to establish and demonstrate an approach for integrating climate change information into project evaluation, ultimately creating a serviceable format from which scientists outside of the climate specialty may address climate risk management decisions. Appraisal of long-term benefits under climate change assists in establishing climate significance and whether a fully inclusive analysis is warranted, especially considering economic variability, policy, and other competing demands. A coupled hydrology–Ethiopian hydropower model is driven by potential climate changes in precipitation and temperature to produce project benefit-cost ratios over 50 years. The B/C ratios are transformed into surface illustrations to assess and compare climate change influences on single or multiple projects. Surface interpretation indicates that drier than historically normal conditions appear to have a greater detrimental effect on overall B/C ratios than the positive effect under wetter than normal conditions. Project outcomes under large discount rates are relatively unaffected by climate change influences, while smaller rates point toward greater potential variability. A doubling of the allowable rate of streamflow impoundment produces decidedly higher B/C ratios throughout the range of climate changes explored.

Although a range of climate change scenarios are explored, a more complete assessment is likely justified through a probabilistic evaluation of historical conditions. In this study, the actual 1951–2000 monthly conditions are repeated in sequence with climate changes imposed on top. Alternatively, an ensemble of 50-yr sequences generated from the 1951–2000 record could be used as starting points to develop multiple plausible B/C ratios for each precipitation and temperature combination. This would effectively give thickness to the surfaces.

Surface illustrations alone may not be sufficient for final decisionmaking, but they begin to give a sense of the influence of climate change independently and in comparison to other factors (policy and economics). Priorities and beliefs as to how future climate may evolve play a critical role in final project appraisal. If the assumption exists that all potential climate change scenarios presented here are equally likely, effectively weighting each scenario uniformly, the surfaces can be interpreted as if in a probability space, and the overall expected B/C ratio is simply an average of the entire surface. However, if some scenarios are believed to be more likely, they may be given a higher weight, skewing the overall expected B/C ratio away from the surface mean. Rationales for weighting scenarios differently may develop from local knowledge or trends, global climate model or Intergovernmental Panel on Climate Change projections, or other sources. Quantifying these weights and applying them to the B/C ratio surfaces is an ongoing piece of research.

Acknowledgments

The authors appreciate the reviews of Dr. Alyssa McCluskey and Dr. Pietro Ceccato.

References

Adger, W.N., S. Huq, K. Brown, D. Conway, and M. Hulme. 2003. Adaptation to climate change in the developing world. Progress in Development Studies 3:179–195.

Block, P., and K. Strzepek. In press. Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate change. Journal or Water Resources Planning and Management.

Bodo, B. 2001. Monthly discharge data for world rivers. University Corporation for Atmospheric Research, Computational and Information Systems Library. [online] URL: dss.ucar.edu/datasets/ds552.1. Accessed 1 July 2008.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. University College London, Department of Geography, London, U.K.

Enfield, D.B., and L. Cid-Serrano. 2006. Projecting the risk of future climate shifts. International Journal of Climatology 26(7):885–895.

Fankhauser, S., J.B. Smith, and R.S.J. Tol. 1999. Weathering climate change: Some simple rules to guide adaptation decisions. Ecological Economics 30(1):67–78.

Frederick, K.D. 1998. Principles and concepts for water resources planning under climate uncertainty. Water Resources Update, Summer:41–46.

James, C., B.T. Bower, and N.C. Matalas. 1969. Relative importance of variables in water resources planning. Water Resources Research 5(6):1,165–1,173.

Mitchell, T., T. Carter, P. Jones, M. Hulme, and M. New. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100). Tyndale Center for Climate Change Research, Working Paper 55, Norwich, U.K.

New, M., M. Hulme, and P.D. Jones. 1999. Representing twentieth century space-time climate variability. Part 1: Development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate 12:829–856.

Rogers, P. 1997. Engineering design and uncertainties related to climate change. Climatic Change 37:229–242.

Thomson, G. 2006. Encyclopedia of the Nations: Africa. Gale Cengage, Farmington Hills, MI.

Yates, D. 1996. WatBal: An integrated water balance model for climate impact assessment of river basin runoff. International Journal of Water Resources Development 12(2):121–139.