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Water Resources Planning under Climate Change

A "Real Options" Application to Investment Planning in the Blue Nile

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Abstract

This article develops a "real options" approach for planning new water resources infrastructure investments and their operating strategies in a world of climate change uncertainty. The approach is illustrated with an example: investments in large new multipurpose dam alternatives along the Blue Nile in Ethiopia. The approach incorporates flexibility in design and operating decisions – the selection, sizing, and sequencing of new dams, and reservoir operating rules. The analysis relies on a simulation model that includes linkages between climate change and system hydrology, and tests the sensitivity of the economic outcomes of investments in new dams to climate change and other uncertainties. Not surprisingly, the results for the Blue Nile basin show that there is no single investment plan that performs best across a range of plausible future climate conditions. The value of the real options framework is that it can be used to identify dam configurations that are both robust to poor outcomes and sufficiently flexible to capture high upside benefits if favorable future climate and hydrological conditions arise. The real options approach could be extended to explore design and operating features of development and adaptation projects other than dams.

Key Words: Nile Basin, real options, dams, climate adaptation, cost-benefit analysis, Ethiopia, Monte Carlo simulation

JEL Codes: D810, O220, Q250, Q420, Q540

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Introduction

The planning of large water resources infrastructures and other similarly long-lived development projects is fraught with uncertainty. Systems-based decision analytic methods for prioritizing among such projects have existed for decades but are infrequently used, and dams in large river basins have historically been designed and built in piecemeal fashion without careful consideration of system-wide consequences [Eckstein, 1958; Hobbs et al., 1997; Jeuland, 2010; Rogers and Fiering, 1986]. Once projects are constructed, systems-level optimization of operating rules for coordinating releases from multiple reservoirs is also rare [Yeh, 1985]. Yet integrated systems planning methods may yield significant economic benefits, ranging from enhanced hydropower uplift at downstream hydropower plants to improved management of system water demands [*Jeuland*, 2009]. The failure to use optimization techniques for planning new investments or management regimes in large river basins is not due to a lack of appropriate tools and models. Many examples of economic optimization models for enhanced river basin planning and management are documented in the academic water resources literature [Harou et al., 2009; Loucks et al., 2005; ReVelle and McGarity, 1997; Tanaka et al., 2006; Wu et al., 2013].

As early as the 1980s Rogers and Fiering [1986] considered why systems models are rarely used in practice. They suggested that this was partly the result of systems optimization techniques developing too late to influence the construction of large dams in the United States and much of the developed world. However, even in developing and middle-income countries where such tools could have been used, water resource planners have not deployed

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them widely. Within technocratic planning agencies throughout the world, there is strong resistance to systems-optimization techniques. This resistance seems partly related to a lack of confidence in the assumptions and structure of optimization models and to concerns over how they handle hydrological, political, and economic uncertainty over the long time horizon that is relevant for such projects. Traditional economic optimization models require that the planner assign *ex ante* specific probabilities to possible future states of the world in order to identify optimal or near-optimal solutions. If no single infrastructure and management strategy dominates others across a range of plausible future conditions, and if it is difficult to assign even subjective probabilities to future states of the world, system economic optimization approaches cannot offer compelling guidance on planning solutions. In addition, narrowly defined optimality rules often seem inappropriate for complicated, multi -objective water infrastructure projects, especially when many near-optimal planning solutions may exist [Rogers and Fiering, 1986]. Finally, a state may decide not to pursue investments deemed optimal for other reasons; state actions may in reality be taken to maximize the private gains of specific individuals or to protect specific individuals' interests.

We argue here that a "real options" framework is one tool that can be useful in dealing with future uncertainties, using the example of the Eastern Nile basin. The approach can help planners better understand how the outcomes of hydro-economic simulations for a potential new infrastructure "alternative," defined as a particular combination of design features and operating rules for a specific configuration of infrastructure projects, might vary across hydrological and water demand "conditions". We do not assess economic optimality across alternatives in a formal sense because we do not believe systems-optimization approaches are likely to be compelling to decision makers. This is because: (1) we find that no single alternative dominates others across a range of such plausible future conditions; and (2) we believe that neither decision makers nor planners are likely to be satisfied with essentially arbitrary probabilities for future climate change outcomes and changes in water withdrawals by riparian states.

In our application of this real options approach, we aim to identify alternatives characterized by design and operational features that are both robust to poor future conditions and allow the capture of higher upside potential should favorable conditions arise [Cardin et al., 2007; De Weck et al., 2004; Dixit and Pindyck, 1994; Wang and de Neufville, 2006]. Using Monte Carlo methods, the economic outcomes of a set of specific alternatives are estimated across different climate change and water withdrawal (development) conditions. We present and then compare these alternatives' economic outcomes using a series of relative measures of downside, expected, and upside performance that facilitate their comparison.

Real options (i.e., design features and operating rules of dams) may arise from the inherent operational flexibility of different infrastructure configurations, or from delaying investments until more information is obtained [Steinschneider and Brown, 2012]. Pursing such options typically entails costs. Because our modeling approach acknowledges the value of options for adaptation to future conditions, it makes little sense to speak of optimal alternatives, as the optimality of these depends on what is assumed about a highly uncertain future. Not only are the probabilities of future states of a water resources system unknown (rendering the calculation of expected benefits impossible), but policy makers and planners are typically risk averse, find subjective probabilities hard to interpret, and are most concerned about downside outcomes, which are often poorly represented in existing hydro-economic optimization models [Harou et al., 2009; Hobbs et al., 1997]. A real options framework that uses simulation methods instead readily provides information on the range of economic net benefits associated with different project alternatives across a variety of possible future conditions. Uncertainties arising from multi-year hydrological variability, the economic value of power or water supply outputs, and other model parameters can then be examined, and the distribution of outcomes of simulations for different climate scenarios and development conditions can be compared. Social, political, and environmental objectives could also be included in definitions of what is considered robust design (although we do not do this in our illustrative example).

The next section provides background regarding our example, describing the hydropolitical context of the planning problem in the Blue Nile, which highlights the need for a decision framework that accounts for physical and economic uncertainties. The succeeding section presents the real options analytical framework and describes our approach for analyzing the Blue Nile investment problem. Sections reporting results and conclusions complete our discussion.

Background

The idea of storing Nile waters in the Blue Nile gorge in Ethiopia has long been on the minds of Nile Basin peoples [Erlikh, 2002]. The river falls rapidly in the narrow canyons of the Blue Nile gorge, offering numerous sites for hydropower generation dams with low surface-to-volume ratios and high head. The first comprehensive plan for dam construction in the Blue Nile gorge was developed more than 50 years ago by the United States Bureau of Reclamation [USBR, 1964], and Ethiopian water resources professionals and international consultants have been studying and refining these plans ever since. Since the late 1990s, in anticipation of a basin-wide cooperative agreement among the riparians that could facilitate international financing of such projects, international consultants working for the Ethiopian Ministry of Water Resources have prepared detailed feasibility studies for several of the most promising dam sites [BCEOM et al., 1998; EDF, 2007a; b; Norplan-Norconsult, 2006].

Over the past several centuries, Egypt has occupied a privileged position regarding the waters of the Nile, supported by its relative geopolitical and economic power [Waterbury, 2002]. Egyptians have long feared that their water rights could be compromised by upstream actions. In particular, Ethiopians have periodically threatened to assert their perceived rights over the Blue Nile. In the past, Ethiopia would have needed financing from international donors to build a major dam in the Blue Nile gorge, as well as aid in technical expertise. Because such water resources investments would have basin-wide consequences, international donors hoped to facilitate a basin-wide agreement on procedures for notification and development of proposed infrastructures. In fact, for over a decade, facilitated by the Nile Basin Initiative (NBI), the Nile riparians have engaged in wide ranging discussions on establishing just such a cooperative framework agreement.

Several recent trends and events have combined to change this centuries-old dynamic in the Eastern Nile. By 2009, the multilateral discussions of the NBI had reached an impasse. The riparians had agreed on virtually all of the language in the draft text of the agreement, except the phrase (referring to the actions of one riparian) “not to significantly affect the water security of any other Nile Basin State.” Egypt and Sudan wanted more explicit acknowledgment of “current uses and rights” to Nile waters, which they argued were legally established under the 1929 and 1959 Nile Waters Agreements. The other upstream countries rejected this position, countering that colonial era agreements could not be considered binding. Negotiations to bridge the gap have to date proven unsuccessful. By early 2011 six upstream riparians had signed the original text of the Cooperative Framework Agreement (the Democratic Republic of Congo still has the matter under consideration, while Egypt and Sudan have not signed).

In addition, there is now much greater expertise and knowledge of how upstream development affects the system-wide behavior of the river and its uses, particularly in Ethiopia. On July 19, 2010, Ethiopian Prime Minister (PM) Meles Zenawi (now deceased) stated in an interview on Egyptian television:

> The first thing to recognize is that utilization of the Nile water is not a zero-sum game. It does not mean that if the upper riparian countries benefit, Egypt and Sudan should lose. . . . It is not difficult to find a win-win solution.

> The Nile water can be used for two purposes. The first purpose is the generation of electricity. The second purpose is for irrigation. In terms of utilization for electricity, no amount of dams built in the upper riparian countries will hurt Egypt or Sudan. On the contrary, if dams are built in Ethiopia, Egypt and Sudan will benefit [Egyptian TV, 2010].

In addition, by early 2011 the hydropolitical balance among Nile riparians had changed. Ethiopia now believes it has the economic strength to marshal the financial resources needed to proceed unilaterally with the construction of an initial dam project in the Blue Nile gorge costing several billion dollars. In the same interview in 2010, PM Meles also declared: "Ethiopia has reached a stage where it can build its own dams with its own money." Equally important, larger political forces have swept over the region. On February 1, 2011, tens of thousands of antigovernment protesters occupied Tahrir Square in the heart of Cairo. On February 2 and 3, anti-government protesters fought with supporters of Hosni Mubarak, President of Egypt, in Tahrir Square, in events that eventually led to his resignation on February 12.

On February 3, 2011, in the midst of these major events, PM Meles announced to the Ethiopian Parliament that his Government had decided to construct a large multipurpose dam on the Blue Nile near the border with Sudan. On February 6, 2011, the Ethiopian Press carried the announcement that Ethiopia would build the "Renaissance Dam" (sometimes called the "Millennium Dam," as well as the "Big Border Dam," because it is near the site of a smaller proposed dam called the "Border Dam" near the Ethiopia-Sudan border) on the Blue Nile near the Ethiopian-Sudanese border. This announcement began a new era in the hydropolitics of the Nile. Elaborating on the theme of the mutual benefits of Blue Nile investments, PM Meles asserted that the Renaissance Dam offered benefits to both Sudan and Egypt even in the absence of formal cooperation, and that downstream riparians should work with Ethiopia on its planning and construction and share in its costs.

In fact, although several observers have argued that water storage in the Blue Nile gorge offers attractive opportunities for the Eastern Nile riparians for joint, multipurpose investments, the economic attractiveness of investments in a Blue Nile cascade has not been carefully analyzed [Blackmore and Whittington, 2009; Tilmant and Kinzelbach, 2012; Whittington et al., 2005]. In part this is because the riparians do not have much incentive to undertake the analytic work necessary to determine the economic consequences of Blue Nile storage to other riparians. The lack of such information partly explains the absence of concrete plans for benefit-sharing. One of the objectives of our discussion here is to offer an economic assessment of investment options for dams on the Blue Nile in Ethiopia under various plausible future climate and development conditions (e.g., water withdrawal). Our real options approach first considers the choice set for infrastructure assuming that the decision to construct the Renaissance Dam had not been made. We then show the consequences of path dependency by comparing development alternatives that include the Renaissance project as the first investment, with the wider set of other (original) alternatives.

Although climate change uncertainty provides much of the motivation for the use of a real options approach, our discussion does not focus on the state of the art for producing temperature and hydrological runoff projections from climate change models. Other researchers have undertaken this task [IPCC, 2007; Leavesley, 1999; Wood et al., 1997; World Bank, 2009]. Instead this analysis explores the sensitivity of the economic benefits of multipurpose dams to increased temperatures consistent with climate projections for this region in the year 2050 (2°–3°C) [Strzepek and McCluskey, 2007] and changing precipitation, with associated linkages to runoff, evaporation, and irrigated crop water requirements [Jeuland, 2010].

The Nile Basin is an interesting location for an application of a real options approach for several reasons. First, as discussed above, there are several attractive sites today for large new multipurpose dams at several locations along the Blue Nile. Second, in spite of recent developments, there is a growing understanding among the riparians of the Blue Nile that upstream regulation may generate system-wide, multipurpose benefits [Blackmore and Whittington, 2009]. Third, although initial research on climate change suggests that arid and semi-arid developing countries are particularly vulnerable to the impacts of climate change [Conway et al., 1996; Deressa, 2007; IPCC, 2007; Strzepek and McCluskey, 2007], there is substantial uncertainty concerning how climate change will impact the Nile [Conway and Hulme, 1996; Sayed and Nour, 2006]. The effect that such uncertainty could have on the economic attractiveness of new projects has not been considered systematically in the literature, either in specific locations such as the Nile Basin, or in general. New or existing infrastructures may play an important role in adaptation to climate change, but little practical research exists to guide planners as to which water resources development paths provide the greatest adaptation benefits.

Evaluation framework and application

The process of planning water resources investments is best conceptualized as a staged problem, in which some decisions, once implemented, provide more flexibility to respond to uncertain changes in future conditions than do others. For example, the choices of dam site and sizing are inflexible, whereas rules for reservoir filling rates and operation can be continuously modified in response to changing conditions. A real options framework can provide structure to the complex problem of considering flexibility within the water resources planning problem. With our Blue Nile application the first task is to define the planning alternatives (and the real options) that are to be modeled. We then describe the simulation model and analytical framework for evaluating the performance of those alternatives.

Planning alternatives and real options

In our analysis, we consider multipurpose dams located at five sites along the Blue Nile – Karadobi, Beko Abo, Mabil, Mendaya, and Border (Figure 1). Pre-feasibility or other identification studies have been completed for all five of these sites [EDF, 2007a; b; EEPCo, 2011; Norplan-Norconsult, 2006; USBR, 1964]. These proposed sites have different relative advantages. Because flow is higher at downstream sites in the gorge, a site like Border could provide the most regulation and water release through hydropower turbines. However, siltation loads would be higher, reducing project lifespan, and evaporation loss would be greater because rainfall is lower in the northern part of the catchment and average temperatures are higher. Also, head would be lower at the Border site than at upstream locations due to less favorable topography. Dams situated farthest upstream (e.g., Karadobi and Beko Abo) would have the most favorable topography, and therefore highest head and lowest reservoir surface area per unit of storage, but would have lower reservoir inflows (for example, the estimated flow at Karadobi would be about 42% of that at Border, judging from historical flows). A site like Mendaya in the middle of the Blue Nile gorge would balance these tradeoffs (the estimated flow at Mendaya would be 71% of the flow at Border).

Table 1 indicates the various combinations of dams for which we simulate economic outcomes. In what follows, a planning "alternative" is defined as a specific combination of design features and operating rules (together comprising "options") applied to a specific configuration of dam projects. Design features include such considerations as dam sequencing, timing, and size; operating rules include maximization of dam-specific energy production and coordination of multiple objectives across dams. As detailed below, we consider a variety of other options – which together yield a total of 350 unique planning alternatives (Table 2):

1. <u>Configuration</u> (I_m). Each of 17 unique configurations (5 with individual dams, and 12 with combinations of them) m is denoted by I_m (Table 1). For example, I_3 indicates an alternative with only Mabil; I_8 is a combination with Karadobi and Mendaya. Not all configurations are feasible, because some downstream dam

reservoirs would flood upstream dam sites (for example, a dam at Beko Abo would flood Karadobi). The configuration option is flexible to the extent that dams built late in a multi-project configuration can be reconsidered until the time when their construction begins.

2. Sequencing (U_n). For multi-dam combinations, we generally assume that the dam farthest upstream would be built first, allowing subsequent projects to benefit from enhanced flow regulation (this is denoted U_0). We relax this assumption when we consider the attractiveness of options following completion of a first dam at the Border site, which corresponds to Ethiopia's recent choice (the 130 alternatives where the downstream Border project is built ahead of upstream projects are denoted U_1).
3. Timing (T_o). For multi-dam combinations, we consider faster successions of projects (T_1, where each subsequent dam begins operation 10 years after the preceding one) and slower successions (T_2, 20 year spacing). The possibility of delaying investment in a second dam from 10 to 20 years after the construction of the first dam introduces flexibility into the planning problem.
4. Size (S_p). Using data from existing pre-feasibility and feasibility studies, three alternative sizes are considered at Mendaya and Border and two are considered for Karadobi, Mabil, and Beko Abo. Table 2 details the notation for other feasible combinations of project sizes (for example, a configuration of projects containing only small dams is identified as S_1). A small design is inflexible, given that dam enlargement is likely technically impossible. However, if the planner opts for a larger dam design, it may be possible to utilize varying amounts of reservoir capacity, should the dam prove too large. Building in flexibility to operate the dam at various levels from the time of construction would require designing multiple intakes to allow for releases through the hydropower turbines under different operating conditions.
5. Operating rule (O_r). We test two operating rules, "hydropower-based" (O_1) and "downstream coordination" (O_2). The hydropower-based rule is derived from the rule curves proposed in pre-feasibility studies, developed using energy generation optimization models and ignoring the potential for multi-reservoir optimization as well as the effects of upstream regulation on downstream riparians. In contrast, the downstream coordination operating rule sets a trigger to force minimum releases from Blue Nile dams if storage in the downstream High Aswan Dam in

> Egypt drops below 60 billion cubic meters (bcm). Increased releases from upstream dams during dry periods could alleviate downstream deficits during periods of system-wide low flows, but at the cost of reduced hydropower production in Ethiopia.

We refer to each specific planning alternative in our total of 350 as a unique package of these five options. For example, an alternative labeled $I_1\_U_0\_T_0\_S_1\_O_2$ refers to a small Karadobi dam operated to coordinate releases with storage levels in Lake Nasser. For simplicity, our presentation here shows direct graphical comparisons of alternatives that contain the same number of dams, although we comment on the relative magnitude of net benefits from combinations with different numbers of infrastructures. Each planning alternative is evaluated for seven hydrological runoff scenarios, ranging from reductions of 15% to increases of 15% over historical conditions, in increments of 5% (labeled by the % change in runoff; for example, –15 or +5), and three assumptions about water withdrawals by Egypt, Sudan, and Ethiopia (labeled W_0 to W_2; see Table 2). The changes in runoff are informed by a close reading of the literature on climate change projections for the Nile Basin (summarized in Table 3), applied in equal proportions to existing inflows along all major reaches of the Nile. Additional water demands (withdrawals) are scattered throughout the basin at the locations indicated in country Master Plans (see Appendix for their locations). These increased water withdrawals have varying impacts on reservoirs at different locations: some are upstream of some or all of the new reservoir sites, others are downstream of them.

Each unique combination of a planning alternative, water withdrawal condition, and runoff scenario is termed a simulation “experiment. In total, we report on the results of 7,350 simulation experiments (350 planning alternatives × 7 runoff scenarios × 3 water withdrawal assumptions). By comparing the performance of planning alternatives across these simulation experiments, we are able to assess: (1) whether there are complementarities among dams; (2) whether real options have a significant influence on the economics of the alternatives; and (3) whether changes in future hydrological or irrigation withdrawal conditions alter conclusions about which alternatives perform best.

The models

Our modeling framework consists of three linked models for stochastic runoff generation, hydrological routing, and Monte Carlo simulation of economic outcomes for the different project alternatives [*Jeuland,* 2010]. These models contain explicit linkages between climate change and runoff, system hydrology and production, and valuation of economic outputs, respectively. In a hydrological routing analysis, for each of the 7,350 experiments described above, 100 separate hundred-year sequences of stochastic inflows are passed through the system. The 100 resulting sets of physical outcomes are then used as inputs to a cost-benefit model in which 5,000 Monte Carlo trials are applied to yield distributions of net present value (NPV) for each experiment. These simulations take random draws from the flow series' of physical outcomes, and from uniform or triangular distributions of uncertain economic parameters (such as the discount rate, capital cost, the value of hydropower, etc.). Thus the parameters for each experiment incorporate both natural hydrological variability and economic uncertainty. The Appendix includes further explanation of the economic costs and benefits included in the model, as well as the locations of new water withdrawals, assumed ranges for uncertain model parameters, and other model details.

Analytical framework for comparing planning alternatives

From the NPV distributions obtained in each Monte Carlo experiment, three economic indicator metrics are selected. These indicators are specific to a planning alternative *j* in a given situation *i* (as defined by runoff and water withdrawal condition):

1. Downside risk, defined as the 10^{th} percentile of the NPV distribution for alternative *j* given *i*;
2. Expected NPV, or the mean value of the NPV for alternative *j* given *i*;
3. Upside potential, defined as the 90^{th} percentile of the NPV distribution for alternative *j* given *i*.

Unfortunately, these simple metrics do not allow easy comparison across planning alternatives, for two reasons. First, multiple planning alternatives may perform well but not dominate one another in terms of these three metrics, in which case other kinds of comparisons become necessary in order to choose between them. Second, economic outcomes for an infrastructure that is operated in a specific way do not account for the adaptive options mentioned previously.

To address these challenges, we first define relative measures for each planning alternative *j*, that permit comparison to the best-performing alternative selected using each of the metrics above under conditions *i* (where these best alternatives may vary across metrics). These relative metrics enable quantification of the relative risks or opportunity costs associated with selecting alternative *j*:

$C_{exp,j,i} = NPV_{exp,i}* – NPV_{exp,j,i}$;(1)

$D_{lost,j,i} = D_i* – D_{j,i}$;(2)

$U_{lost,j,i} = U_i* – U_{j,i}$; where(3)

$C_{exp,j,i}$= expected opportunity cost of selecting alternative *j* in situation *i*;

$NPV_{exp,i}$*= expected net present value of the planning alternative with the highest expected NPV in situation *i*;

$NPV_{exp,j,i}$= expected net present value of alternative *j* in situation *i*;

$D_{lost,j,i}$= decrease in downside NPV associated with alternative *j* relative to the alternative with the highest downside NPV in situation *i* (10^{th} percentile of the NPV distribution);

D_i*= 10^{th} percentile NPV of the alternative with the highest upside in situation *i*;

$D_{j,i}$= 10^{th} percentile NPV of alternative *j* in situation *i*;

$U_{lost,j,i}$ = decrease in upside NPV associated with alternative *j* relative to the alternative with the highest upside NPV in situation *i* (90^{th} percentile of the NPV distribution);

U_i*= 90^{th} percentile NPV of the project alternative with the highest upside in situation *i*;

$U_{j,i}$= 90^{th} percentile NPV of project *j* in situation *i*.

Next, we modify the calculation of metrics to account for the possibility of design and operational flexibility; i.e. $C_{exp,j,i}$ is replaced with the expected cost $C_{flex,exp,j,i}$ of alternative *j* with flexibility in situation *i*:

$$C_{flex,exp,j,i} = \text{Min}[C_{exp,1,i} + \chi_{1,j}; C_{exp,2,i} + \chi_{2,j};\ldots C_{exp,j-1,i} + \chi_{j-1,j}; C_{exp,j,i}; C_{exp,j+1,i} + \chi_{j+1,j};\ldots; C_{exp,J,i} + \chi_{J,j}], \quad (4)$$

where $\chi_{k,j}$ is the cost of converting alternative *j* into alternative *k*. We assume for simplicity that: (1) changes in operating rules are costless; (2) smaller dams cannot be converted into larger dams; but (3) larger dams can be operated as if they were smaller dams. The cost of this “operational downsizing” is assumed to equal the sum of the additional capital investment required for the larger project plus the reduced (discounted) benefits of the smaller project due to the *t* extra years required for building the larger project (equation 5). This is a lower bound on the costs of flexibility, because downsizing would also require the construction of multiple hydropower intakes, and in building capacity for enhanced adaptation of operating rules.

$$\chi_{k,j} = \left\langle \begin{array}{ll} 0 & \text{if } k \text{ and } j \text{ differ merely by operation, or } j = k \\ \left(\kappa_j - \kappa_k\right) + B_k / (1+\delta)^{t_{jk}} & \text{if } j \text{ is larger than } k \\ \infty & \text{if } j \text{ is smaller than } k, \end{array} \right. \tag{5}$$

where κ_j = net present value of the capital cost of alternative *j*;

B_k= net present value of benefits of alternative *k*;

δ= discount rate;

t_{jk}= additional time required to construct alternative *j* relative to *k* (in years).

We then assess whether $C_{\text{flex,exp},j,i} < C_{\text{exp},j,i}$, such that alternative *j* with flexibility becomes more attractive given its relative performance in situations where the nonflexible alternative *j* performs poorly. Thus, the only extra computational effort needed to account for the costs of flexibility is to store the values of discounted capital costs simulated in the Monte Carlo experiments for each alternative *j* given situation *i*, and to use these to adjust the relative metrics as shown in equations 4 and 5. The relative upside and downside for each alternative *j* and situation *i* can be adjusted in similar fashion. Project risks can then be compared with the expected or upside potential of the alternatives, within and across the modeled conditions.

Using this approach, risk-reward tradeoffs can be compared across alternatives. For example, building a small dam may be a low risk–low upside choice under current climate and demand conditions. This important tradeoff between risks and rewards would be masked by typically used measures of expected outcome. In addition, economically inferior alternatives that consistently lie below the low risk–high reward frontier (i.e., that neither minimize risks nor maximize upside, or expected, net benefits) can be eliminated. The relative metrics can also be used to explore the cost of delaying investments. The most obvious alternative to acquiring flexibility using real options is to wait for uncertainty to partially or fully resolve itself. Using the modeling framework developed above, one can test the hypothesis that delay combined with enhanced information could be economically justified. Finally, one can evaluate the tradeoffs involved in choosing specific development paths, for example, favoring irrigation over hydropower generation, or making a politically motivated investment decision.

Results

We begin by summarizing how the “best” infrastructure, defined using the simplest expected NPV metric, is sensitive to model conditions, assuming that inflow scenario probabilities are known. We then show how economic outcomes and the risk-reward tradeoffs vary across hydrological and water withdrawal conditions. The performance of the flexible planning alternatives is then compared using the relative measures defined above. The analysis concludes with an assessment of the value of waiting for more information about future inflows, and of the implications of the initial investment in the Renaissance Dam. The results presented below are of course dependent on the assumptions concerning costs and benefits presented in the Appendix to this paper.

The “best” infrastructures with known inflow scenario probabilities

To investigate the extent to which a specific planning alternative dominates the others, we begin by assuming that inflow condition probabilities are known, and identify which alternative performs best as these probabilities change. For purposes of illustration we restrict the choice set by only allowing the configuration and sizing options to change. Adding the other options does not qualitatively change results, but it does make it more difficult to present the full details for the best alternatives in a single table. We find that the configuration of dams remains relatively stable but, not surprisingly, that the best choice for size (in terms of expected NPV) is sensitive to these assumed inflow probabilities (Table 4). As expected, smaller storage projects perform better when inflows are low and upstream withdrawals are high, because energy production drops and reservoir filling takes longer. Larger storage projects perform better under the opposite circumstances, because capital costs are greater for larger dams. It thus takes more hydropower generation to overcome this higher initial capital expense. Smaller designs also tend to perform better when system withdrawals increase, because the filling time of large upstream reservoirs increases when system demands are higher, and because upstream water withdrawals reduce hydropower production.

These results have important implications for the phasing and sequencing of a multi-dam investment path in the Eastern Nile. The best three-dam combinations generate the highest expected NPV and more frequently include a small Beko Abo design than the single-dam planning alternatives. Indeed, the small Beko Abo option alone only appears once in Table 4 (Case A, with high withdrawals), whereas it appears 3 times for two-dam alternatives and 9 times for three-dam planning alternatives. There are similar differences in the sizes of the best second and third investments. Another important result concerns the robustness of the preferred of two- and three-dam configurations. In 12 cases, the large Border dam (i.e., the Renaissance Dam) appears in the best two-dam configuration; however, Renaissance precludes the most attractive three-dam combinations (because it floods Mendaya). As explained further below, a two-dam alternative that includes the Renaissance (large Border) dam therefore corresponds to a significant loss of expected NPV.

The risk-reward space for the planning alternatives

The three economic metrics for all planning alternatives vary substantially across climate and development scenarios. As expected, lower inflows and higher withdrawals for upstream irrigation can result in greatly decreased expected NPV, because they decrease both storage levels and flows through the hydropower turbines and in the downstream system (Figure 3). Nonetheless, all 350 planning alternatives have positive expected NPV across flow and demand conditions. The best expected NPV is generated by three-dam alternatives that include Beko Abo, Mendaya, and Border, but the sizes of the dams in these best multi-dam combinations are sensitive to these conditions. In a comparison of the planning alternatives that include only a single dam, Beko Abo always has the highest expected NPV. Among two-dam alternatives, Beko Abo + Border (varying sizes), is most attractive. The four-dam combination, which requires a small dam at Mendaya and no project at Beko Abo, is consistently dominated by the best two- and three-dam combinations. Because this combination performs poorly in terms of downside risk and upside potential (results not shown), we do not discuss the four-dam cascade below.

The nature of the tradeoff between risks (10^{th} percentile NPV) and rewards (90^{th} percentile NPV) changes dramatically across basin conditions, and there are many inferior options lying below the low risk–high reward frontier in each case (Figure 2). When inflows increase by 15%, there is little tradeoff: the alternative with the highest upside has only slightly lower downside NPV than the one with highest downside NPV, and vice versa. There is also little cost associated with additional upstream withdrawals in this case. If climate change does not alter runoff, the tradeoff remains small unless upstream irrigation withdrawals also increase. Under W_1 (or W_2) conditions, the highest upside alternative has a downside NPV that is US$2 (or $3) billion worse than the lowest risk alternative (in 2011 US$). With a 15% decrease in inflows, there is a substantial tradeoff across all three withdrawal conditions. Under W_0 withdrawals, the highest upside project is about $5 billion worse in terms of downside NPV than the most conservative one, and this gap increases to more than $6 billion for W_2 conditions. Indeed, the high upside alternative has a slightly negative downside NPV in this case. Importantly, none of the alternatives with highest upside or lowest downside risk include the Renaissance Dam, which appears to have far more storage and energy-generating capacity (and therefore capital cost) than is needed given the water volume carried by the Blue Nile.

Comparison of infrastructure bundles with flexibility

As shown above, the best-performing alternatives (measured in terms of expected NPV) vary across plausible future changes in climate and water demands. The complexity increases as we incorporate options other than size and configuration – sequencing, timing, and operating rules – and their flexibility. The comparisons presented thus far do not allow for clear determination of the specific bundle of options contained in the more favorable alternatives, with the exception of timing and site selection. However, a rapid succession of dam building (option T_1) is always preferred to a slow one (T_2), due to the forgone NPV incurred during delay. The best alternatives all tend to contain dams at the following sites: Beko Abo (single dams), Beko Abo + Border (two dams), and Beko Abo + Mendaya + Border (three dams).

The best alternatives for various combinations are summarized in Table 5 for conditions that create the lowest downside (-15_W_2), the greatest upside ($+15\_W_0$), and show expected NPV for conditions in the middle ($+0\_W_1$). To assess the relative performance of different alternatives more extensively, we compare the relative metrics for the alternatives across scenarios, accounting for flexibility. We begin with single-dam alternatives, then add additional dams in sequential fashion, though we note that the three-dam alternatives are almost always most attractive. Among single-dam alternatives, the expected cost, relative to the best alternative, of building the medium Beko Abo ($I_2\_S_2$), is nearly always zero (Figure 4, top panels). A small Beko Abo ($I_2\_S_1$) outperforms this medium size only if both upstream withdrawals are high (W_2) and runoff is low (–15%), but its relative performance under more favorable flow conditions declines significantly (US$8 billion of expected NPV is lost if runoff increases 15%). Other relatively attractive single-dam alternatives are medium or large Border ($I_5_S_2$ and $I_5\_S_3$), and medium or large Mendaya ($I_4\_S_2$ and $I_4\_S_3$), but these produce $3 billion–$7 billion less NPV across model situations than medium Beko Abo. In general, larger dams perform better when withdrawals are low and flows are high, and smaller dams perform better in the opposite case. Mabil is not shown, as it is far inferior to the other single-dam alternatives.

Considering downside rather than expected NPV improves the relative performance of two alternatives compared to medium Beko Abo ($I_2\_S_2$): medium Border ($I_5\_S_2$) and small Beko Abo ($I_2\_S_1$) (Figure 3, middle panels). $I_2\_S_1$ performs better in terms of downside NPV when runoff is reduced by more than 5% (the relative advantage over $I_2\_S_2$ is US$1 billion–$1.5 billion when runoff declines by 15%), but its downside is $3 billion–$4 billion worse under the highest flow conditions. By the same metric, the $I_5\_S_2$ dam is $2 billion–$4 billion worse than $Inf_2\_S_2$ across flow and withdrawal conditions. A conservative strategy seeking to hedge against the worst potential outcomes would therefore favor an initial investment in a small Beko Abo project (because relative returns from this project are negatively correlated with changes in runoff).

A risk-taking strategy, on the other hand, would favor medium Beko Abo ($I_2\_S_2$). The relative upside of this option is highest across conditions (Figure 3, bottom panels). The relative upside NPV lost with the conservative small Beko Abo ($Inf_2\_S_1$) ranges from US$2 billion (when runoff is reduced 15%) to $25 billion (15% runoff increases), and the other most attractive options (medium and large Border/Renaissance and Mendaya projects) are $6 billion–$10 billion worse than $I_2\_S_2$ in terms of this metric. Given that increases in flow are possible in the Blue Nile, there could be significant lost economic opportunities from choosing designs that minimize relative risks. Furthermore, the relative advantage of Beko Abo alternatives actually increases with withdrawals. This is because few of the additional irrigation withdrawals occur upstream of Beko Abo (see Appendix), such that flow through its turbines is less affected by these developments than that at alternatives farther downstream (i.e., Mendaya or Border).

Medium Beko Abo seems highly attractive when considered alone, but this advantage is less obvious for the two-dam alternatives (Figure 5). In terms of relative expected and upside NPV, medium Beko Abo plus large Border/Renaissance ($I_{11}\_S_7$) performs best when runoff increases. With lower or historical runoff, however, medium Beko Abo and medium Border ($I_{11}\_S_2$) is usually best. $I_{11}\_S_2$ has the highest downside NPV when runoff increases, whereas small Beko Abo and small Border ($I_{11}\_S_1$) is best when runoff decreases. Medium Beko Abo + small Border ($I_{11}\_S_6$) looks attractive across flow scenarios. In fact, the loss of relative downside of the more risk-taking $I_{11}\_S_7$ combination increases quickly when flows are reduced, reaching US$5 billion with a 15% reduction in flows. Among two-dam alternatives with dams other than Beko Abo and Border, combinations including Beko Abo and Mendaya are best. These configurations generally produce $3 billion–$6 billion less in terms of expected NPV than the best Beko Abo and Border combinations, and $1–2 billion less in downside NPV. When runoff declines by 15%, the best Beko Abo plus Mendaya alternatives also outperform the riskier, higher upside $I_{11}\_S_7$ alternative by as much as $3 billion in downside NPV, and $1 billion–$2 billion in expected NPV. Alternatives including Karadobi and a second dam are much less attractive.

Importantly, the risk-taking alternative – medium Beko Abo plus large Border/Renaissance ($I_{11}\_S_7$) – also eliminates the best three-dam configurations that also contain Mendaya (Mendaya is flooded by the Renaissance Dam). These three-dam combinations generate an additional US$2 billion–$4 billion of expected NPV, even though it takes a long time for a third project to come online. The three-dam alternative with the highest expected and upside NPV most typically contains Beko Abo, Mendaya, and Border with all medium sizes ($I_{16}_S_2$) (Figure 5). Under highly reduced flows, the three-dam alternative with all small sizes ($I_{16}_S_1$) is best in terms of expected value, followed by the I_{16}-$\_S_6$ and $I_{16}\_S_4$ combinations that have a mix of small and medium projects (which fare somewhat better than $I_{16}\_S_2$). In terms of downside, the relative advantage of combinations with smaller dams relative to the riskier $I_{16}\_S_2$ alternative increases more sharply, reaching about $4 billion when flows are low and withdrawals high (–15_W_2). Three-dam combinations including Karadobi are less attractive than those with Beko Abo.

It is worthwhile to consider the effect of different operating rules on economic outcomes. Our simulation results show that the most favorable operating rule varies greatly across model conditions (Table 6). Coordinated releases or operation of larger dams at reduced levels decreases hydropower production from the Blue Nile dams, but this coordination sometimes improves economic outcomes by mitigating demand shortfalls downstream. In terms of highest expected NPV, releases coordinated to meet shortfalls in downstream demand are favored for the majority of cases (38/63, or 60%). Allowing coordinated releases with storage levels in Lake Nasser also increases downside NPV in a similar percentage of cases (37/63; results not shown). It is likely that other coordination schemes (perhaps developed using stochastic optimization methods) would fare better than the ad hoc strategies modeled here.

We use these collective comparisons to identify conservative, balanced, and risky investment strategies for Blue Nile hydropower development. With a single dam, the choice is straightforward: small Beko Abo is clearly conservative, whereas medium Beko Abo is a balanced choice that also has the highest upside. For two-dam combinations, a balanced choice is medium Beko Abo plus medium Border. The conservative choice favors smaller designs of these dams, and a risk-taking strategy selects a combination with the large Border/Renaissance Dam. For three-dam combinations, the most balanced choice is a combination with small Mendaya sandwiched by medium Beko Abo and medium Border, whereas conservative and risk-taking choices instead have all three as small and medium sizes, respectively. The large Border/Renaissance Dam does not appear in these three-dam combinations.

The cost of Renaissance Dam and the value of delay

Ethiopia has already committed to building the Renaissance Dam, so we next compare the best alternatives with large Border/Renaissance (allowing for the inclusion of additional dams) to the preferred combinations identified above. The lost expected value for these best Renaissance alternatives, relative to the more economically attractive three-dam cascade with Beko Abo, Mendaya and a smaller dam at Border, ranges US$3 billion–$7 billion across model conditions (Figure 6). Upside decreases by $6 billion–$13 billion, and downside is lowered by $1–$4 billion. These costs are even higher if Renaissance is also operated at capacity (without downsizing flexibility). In this case, the loss of expected NPV increases to $4 billion–$8 billion, lost upside to $9 billion–$15 billion, and downside to $2.5 billion–$7 billion. Alternatives including the Renaissance Dam are less attractive because the project has high capital costs, has lower economic returns than Beko Abo as an initial investment, and eliminates the best three-dam cascade alternative.

One option for dealing with uncertainty would be to delay investments. We consider three simple comparisons for the purpose of illustrating the costs (or value) of delay, applying a real (i.e., net of inflation) social rate of discount of 4% to calculate the expected NPV after waiting. Specifically, we assume that uncertainty over mean changes in future inflows and demands would be resolved in a specific number of years *x*. We then compare the decrease in the expected NPV from implementing the known "best" option under specific and known conditions (after *x* years) with the decrease in expected NPV from immediately implementing the three previously identified investment strategies – balanced, conservative, and risk-taking. This comparison shows that the decrease in expected NPV from waiting relative to the decrease in expected NPV from following a balanced strategy immediately is high. Waiting even five years would be more costly than starting construction now, no matter which inflows and demands materialize, because of the forgone benefits from delaying investment (Figure 7, panel A; similar results apply to the D_1 withdrawal condition). Because nobody expects uncertainty over future climate change to be resolved in anything like five years, a balanced strategy is clearly better than delay. Subsequent investments beyond the initial dam (in this case medium Beko Abo) could still be modified as more information is obtained, noting that outcomes for multiple dams on the same river would be highly correlated because of correlations among the parameters that affect costs and benefits (e.g., flow conditions, local construction costs, the value of energy).

For the conservative strategy with all small infrastructures, waiting five years is an improvement only if inflows increase more than 5% and the investment is limited to the conservative single or two-dam alternative (Figure 7, panel B). Similarly, if withdrawals remain low in the future, the cost of waiting decreases, because the conservative strategy performs less well. Importantly, the conservative three-dam cascade alternative (with small dams at Beko Abo, Mendaya, and Border) dominates a strategy of delay. Also, the conservative strategy outperforms the waiting strategy across all conditions if the waiting time is increased to just seven years.

Finally, consider the risk-taking strategy. As with the balanced strategy, the expected NPV of the "best" projects with waiting a mere five years never outperforms this risk-taking approach, and the amount of forgone benefit increases as flow conditions improve and withdrawals decrease (Figure 7, panel C). Only when water withdrawals increase to W_2 levels, and flows decrease by 10% or more, does delay outperform the risk-taking strategy, for all three (single, two-dam, and three-dam) configurations (results not shown). It therefore seems unlikely that a waiting strategy would outperform any of the three strategies for Blue Nile hydropower development described above.

Discussion

The results of these analyses provide important insights into the economics of infrastructure investments on the Blue Nile, and into how climate change uncertainty can be incorporated into infrastructure planning more generally. The results provide strong support for the decision to move forward with the construction of an initial dam in the Blue Nile cascade. For all reasonable investment strategies and a realistic time horizon for obtaining more information about hydrological change and development uncertainties, the economic costs of delay are greater than the benefits associated with obtaining that information. However, the best alternatives, which include three dams, do not include the Renaissance Dam, but rather include a smaller infrastructure at the Border site. If only two dams could be built (for financial or other reasons), two-dam combinations with Renaissance as one component might perform best if flows increased and water withdrawals in Ethiopia remain low, which does not seem likely and creates an important economic tradeoff – between hydropower and irrigation – for Ethiopia. From this perspective, Egypt should be pleased with PM Meles' choice, even though the large storage volume of the reservoir created by the Renaissance Dam does create opportunities for strategic behavior and adverse filling effects.

Assuming the Renaissance Dam will be built, our analyses suggest that a two-dam combination with Beko Abo as the second project is likely the best alternative for a Blue Nile cascade. Yet our results show that the Renaissance Dam has significant disadvantages across all model conditions relative to the best-performing three-dam alternatives (whether one examines downside, upside, or expected NPV). These costs stem from that project's high capital costs, lower net benefits relative to Beko Abo as an initial investment, and the fact that it reduces the viability of the best three-dam cascade alternatives that contain dams at Mendaya. Even if Renaissance is operationally downsized to make room for Mendaya, these first two disadvantages make alternatives containing it considerably less attractive.

The analysis presented here also provides more general insights. First, new approaches are needed for infrastructure investment planning in a world of climate change. Uncertainties related to future water demands and climate change were shown to have a large effect on the net economic benefits of large hydropower dams. Lower runoff and greater water withdrawals both decrease hydropower production and increase filling time and, from a basin-wide perspective, increase downstream pressure in a hydrological system. These factors decrease the economic returns from dams, particularly larger ones. Second, even when the sites represented in the best alternatives (in this case the three-dam configuration with Beko Abo, Mendaya, and Border) are relatively stable across inflow and water demand conditions, the specific options (size, operating rules, etc.) implemented at those sites are sensitive to those conditions. Third, the sensitivity of infrastructure choice to hydrological and withdrawal conditions throughout the Nile has important implications for the sequencing of investments. Along the Blue Nile, the potential advantages of large dams always decrease when multiple investments are made, even if future inflows increase, and especially when system water demands increase (or if greater emphasis is placed on downside risk). This is partly due to the fact that resettlement from nearly all Blue Nile dam sites would be low, such that additional small dams would not amplify resettlement costs.

Fourth, incorporating flexible options does reduce risks and increase expected net benefits for many alternatives. If higher-risk investments (larger dams) can be designed to be operated as smaller ones – that is, if operating capacity can be varied to handle fluctuations in inflow or demand – the additional capital costs of the larger investments may be justified by higher downside or expected NPV under some future conditions. The value of incorporating flexibility into project design depends on the relative balance of its capital costs and the extent to which it moderates poor outcomes. In this sense, careful study now appears warranted to assess whether the Renaissance Dam could be modified for operation more suited to a multi-dam investment strategy under changing flow and development conditions. And of course, the flipside of this infrastructure flexibility is enhanced demand and operational management: poor outcomes could be avoided through more effective management of system water withdrawals and coordinated or changed release patterns from reservoirs. The speed with which these institutional rules can be altered to respond to evolving climatic and water withdrawal conditions, which depends on cooperation to share benefits and mitigate risks among stakeholders, will determine the potential gains from flexibility.

Although the framework for analysis developed in our exposition here is general, a number of limitations can be identified in our Blue Nile application. One is our assumption that the capacity to adapt management rules and to downsize large dams would not entail significant costs outside of capital and increased construction time. A second limitation is that the sensitivity to climate conditions incorporated into our analysis is not based on the very latest results from available climate models (which are constantly being updated) but is instead informed by published work using such projections. It should thus represent only the range of possible changes that might occur over the medium-term (50–75-years) planning horizon for new dams. Perhaps most importantly, as with all hydro-economic models, the framework implemented here relies on a set of important assumptions. For example, we use the most complete data available to monetize basin-wide impacts of Blue Nile hydropower projects to date, but such data remain limited. However, as we have shown, waiting for better information is costly. Similarly a very specific set of flexible options has been modeled, which does not consider additional operating rules and design features like filling rates, changes in turbine capacity, and different sequencing of projects. More generally, we have focused on aggregate economic outcomes and have not examined their distribution across countries and economic sectors. Nonetheless, the value of a real options framework lies both in its usefulness for systematically considering the different features of various planning alternatives under uncertainty, and in the information it can provide to decision makers who may place more or less weight on downside or upside performance.

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Table 1. Summary of project features and nomenclature system

Project Feature	Single Dams	2-Dam Cascade	3-Dam Cascade	4-Dam Cascade
Dam(s): I_m [a] m = 0 is the "no dam" baseline	m = 1: Karadobi m = 2: Beko Abo m = 3: Mabil m = 4: Mendaya m = 5: Border	m = 7: Karadobi + Mabil m = 8: Karadobi + Mendaya m = 9: Karadobi + Border m = 10: Beko + Mendaya m = 11: Beko + Border m = 12: Mabil + Border m = 13: Mendaya + Border	m = 14: Karadobi + Mabil + Border m = 15: Karadobi + Mendaya + Border m = 16: Beko + Mendaya + Border m = 17: Mabil + Mendaya + Border	m = 18: Karadobi + Mabil + Mendaya + Border
Timing: T_o [b]	n = 0: No timing feature	n = 1: Year 1, 11 n = 2: Year 1, 21	n = 1: Year 1, 11, 21 n = 2: Year 1, 21, 41	n = 1: Year 1, 11, 21, 31 n = 2: Year 1, 21, 41, 61
Sizing: S_p [c]	p = 1: Small p = 2: Medium p = 3: Large	p = 1: All small p = 2: All medium p = 4: Small 1, medium 2 p = 5: Small 1, large 2 p = 6: Medium 1, small 2 p = 7: Medium 1, large 2 p = 8: Large 1, small 2 p = 9: Large 1, medium 2	p = 1: All small p = 2: All medium p = 4: Small 1, others medium p = 5: Large 2, others small p = 6: Small 2, others medium p = 7: Large 2, others medium p = 10: Small 3, others medium p = 11: Large 3, others medium p = 12: Large 3, others small	p = 1: All small p = 13: Small 3, others med
Operating Rule: O_r [d]	r = 1: Standard (Max HP) r = 2: Strong coordination	r = 1: Standard (Max HP) r = 2: Strong coordination	r = 1: Standard (Max HP) r = 2: Strong coordination	

[a] Not all combinations are possible with all sizes due to some upstream sites being flooded by larger downstream dams (e.g. a large dam at Border eliminates the option of a dam at Mendaya).

[b] Slower timing T_2 was found to yield inferior NPV and was only explored for the middle-size dam combinations and hydropower operating rule.

[c] Large sizes are only considered for Mendaya and Border; only two sizes are modeled for the other three sites due to limitations of previous studies.

[d] With strong coordination, the Blue Nile reservoirs release more water when storage in the High Aswan Dam drops below 60 bcm. Specifically, minimum releases are increased to the following levles: Karadobi = 1; Beko Abo = 1.2; Mabil = 1.2; Mendaya = 2; Border = 2.4 (all in bcm/month).

Table 2. Summary of planning alternatives and experiments

Developed Sites	**Number of Alternatives**	**Description**
Karadobi	4	Sizing (2), coordination (2)
Beko Abo	4	Sizing (2), coordination (2)
Mabil	4	Sizing (2), coordination (2)
Mendaya	6	Sizing (3), coordination (3)
Border	6	Sizing (3), coordination (3)
Karadobi + Mabil	10	Sizing (4), timing (1), coordination (5)
Karadobi + Mendaya	14	Sizing (6), timing (1), coordination (7)
Karadobi + Border	28	Sizing (6), sequencing (6), timing (2), coordination (14)
Beko + Mendaya	14	Sizing (6), timing (1), coordination (7)
Beko + Border	28	Sizing (6), sequencing (6), timing (2), coordination (14)
Mabil + Border	28	Sizing (6) , sequencing (6), timing (2), coordination (14)
Mendaya + Border	28	Sizing (6), sequencing (6), timing (2), coordination (14)
Karadobi + Mabil + Border	52	Sizing (12), sequencing (12), timing (2), coordination (26)
Karadobi + Mendaya +	52	Sizing (12), sequencing (12), timing (2), coordination (26)
Beko + Mendaya + Border	52	Sizing (12), sequencing (12), timing (2), coordination (26)
Mabil + Mendaya + Border	16	Sizing (4), sequencing (4), coordination (8)
Karadobi + Mabil + Mendaya + Border	4	Sizing (1), sequencing (1), coordination (2)
Total	350	
Experimental conditions	**# of conditions**	**Description**
Water withdrawal conditions (Status quo, moderate and high development)	3	W_0: Existing water withdrawals and regulating infrastructures W_1: W_0 demands + half of potential expansion in Master Plans for Sudan and Ethiopia up to 1959 treaty allocations (for Sudan) W_2: W_0 demands + all of potential expansion in Master Plans for Sudan and Ethiopia up to 1959 treaty allocations (for Sudan)
Hydrological conditions	7	Range from –15% to +15% of mean annual historical runoff in increments of 5%
Total	21	

Note: Coordination rule considered for all sizes, sequences, and timing; timing option only considered for medium-size dam combinations.

Table 3. Summary of studies of historical climate trends and future projections for the Nile Basin

Source	Analysis	Summary
Elshamy et al., 2000	TAR Projections (2050)	2°–4.3° C increase over Nile Basin; 3°–4° C increase in Northern Sudan and Egypt –22 to +18% change in precipitation
Conway, 2000	Historical trends	No precipitation trend over Blue Nile
Hulme et al., 2001	Historical trends (20th Century)	0.5° C increase in Africa, 0.6° C in Ethiopia
Nyssen et al., 2004	Historical trends	No precipitation trend over highlands in Ethiopia / Eritrea
Sayed and Nour, 2006	TAR Projections	–2 to +11% change in Blue Nile precipitation; –1 to +10% change in White Nile precipitation –14 to + 32% inflows to Lake Nasser
SNC-Lavalin, 2006	TAR Projections for A1B (2050)	+7.4% mean increase in precipitation in Equatorial Lakes (Range: +4.3 to 14.2%) +23% change in inflows to Southern Nile (Range: +4 to 37%)
IPCC, 2007	AR4 Projections	Increased rainfall over Nile Equatorial Lakes Region, GCMs inconsistent over Ethiopia and Sahel
Conway et al., 2007	AR4 Projections for A2, B1 (2050)	+2.2° C mean increase in Ethiopia (Range: +1.4 to 2.9) +1% to 6% mean increase in precipitation in Ethiopia
Beyene et al., 2007	AR4 Projections (Three periods)	Mean precipitation: +15% (2010–2039); –2% (2040–2069); –7% (2070–2099) Inflows at Aswan: –16% (2070–2099)
Elshamy et al., 2008	AR4 Projections for A1B (2081-2099)	2-5° C increase over Nile Basin +2.4% change in precipitation (Range: –15% to +14%) +2-14% increase in potential evapotranspiration –15% mean change in runoff (Range: –60 to +40%)
McCluskey, 2008	TAR Projections for A2, B2 (2050, 2080)	Slight mean increases in precipitation; decreases in runoff

Table 4. Stability of "best" infrastructure choices under different water withdrawal conditions, given changing inflow scenario probabilities, in terms of expected NPV (Expected NPV and risk of NPV < 0 in parentheses, in billions of US$ and %, respectively). Dark lines indicate where "best" decisions change.

Case	Inflow Scenario Probabilities							W_0 = Status quo withdrawals			W_1 = Moderate increase in withdrawals			W_2 = High increase in withdrawals		
	-15%	-10%	-5%	+0%	+5%	+10%	+15%	1 Dam	2 Dams	3 Dams	1 Dam	2 Dams	3 Dams	1 Dam	2 Dams	3 Dams
A	1							Med. Beko (18.3, 0.04)	Sm. Beko + Sm. Bord (24.7, 0.12)	Sm. Beko + Sm. Mend. + Sm. Bord. (26.4, 0.36)	Med. Beko (17.1, 0.66)	Sm. Beko + Sm. Bord (22.9, 1.2)	Sm. Beko + Sm. Mend. + Sm. Bord. (24.5, 1.3)	Sm. Beko (15.4, 1.8)	Sm. Beko + Sm. Bord (21.1, 2.6)	Sm. Beko + Sm. Mend. + Sm. Bord. (22.6, 2.4)
B	1/2	1/2						Med. Beko (20.0, 0.03)	Med. Beko + Sm. Bord (27.3, 0.23)	Sm. Beko + Sm. Mend. + Sm. Bord. (28.9, 0.19)	Med. Beko (19.2, 0.33)	Med. Beko + Sm. Bord (25.5, 0.94)	Sm. Beko + Sm. Mend. + Sm. Bord. (27.1, 0.74)	Med. Beko (17.3, 1.1)	Med. Beko + Sm. Bord (23.2, 2.2)	Sm. Beko + Sm. Mend. + Sm. Bord. (24.8, 1.6)
C	1/3	1/3	1/3					Med. Beko (21.8, 0.03)	Med. Beko + Sm. Bord (29.8, 0.15)	Med. Beko + Med. Mend. + Med. Bord. (32.0, 1.4)	Med. Beko (21.0, 0.33)	Med. Beko + Sm. Bord (28.0, 0.63)	Sm. Beko + Sm. Mend. + Sm. Bord. (29.5, 0.49)	Med. Beko (19.2, 0.75)	Med. Beko + Sm. Bord (25.5, 1.5)	Sm. Beko + Sm. Mend. + Sm. Bord. (27.0, 1.1)
D	1/4	1/4	1/4	1/4				Med. Beko (23.2, 0.02)	Med. Beko + Med. Bord (32.1, 0.37)	Med. Beko + Med. Mend. + Med. Bord. (34.9, 1.1)	Med. Beko (22.4, 0.17)	Med. Beko + Sm. Bord (29.9, 0.47)	Med. Beko + Med. Mend + Med. Bord (31.6, 2.7)	Med. Beko (20.6, 0.57)	Med. Beko + Sm. Bord (27.3, 1.2)	Sm. Beko + Sm. Mend. + Sm. Bord. (28.9, 0.8)
E	1/5	1/5	1/5	1/5	1/5			Med. Beko (25.3, 0.02)	Med. Beko + Med. Bord (35.4, 0.30)	Med. Beko + Med. Mend. + Med. Bord. (38.6, 0.9)	Med. Beko (24.9, 0.13)	Med. Beko + Med. Bord (33.3, 1.1)	Med. Beko + Med. Mend + Med. Bord (35.8, 2.1)	Med. Beko (23.0, 0.45)	Med. Beko + Sm. Bord (30.6, 0.92)	Med. Beko + Med. Mend + Med. Bord (32.6, 3.7)
D	1/7	1/7	1/7	1/7	1/7	1/7	1/7	Med. Beko (28.7, 0.01)	Med. Beko + L. Bord (41.0, 0.94)	Med. Beko + Med. Mend. + Med. Bord. (44.4, 0.6)	Med. Beko (28.6, 0.09)	Med. Beko + Med. Bord (39.3, 0.77)	Med. Beko + Med. Mend + Med. Bord (42.4, 1.5)	Med. Beko (27.0, 0.32)	Med. Beko + Med. Bord (36.3, 1.5)	Med. Beko + Med. Mend + Med. Bord (39.2, 2.6)
E			1/5	1/5	1/5	1/5	1/5	Med. Beko (32.1, 0.0)	Med. Beko + L. Bord (47.3, 0.01)	Med. Beko + Med. Mend. + Med. Bord. (50.8, 0.0)	Med. Beko (32.3, 0.0)	Med. Beko + L. Bord (45.8, 0.16)	Med. Beko + Med. Mend + Med. Bord (49.1, 0.09)	Med. Beko (30.9, 0.01)	Med. Beko + Med. Bord (41.9, 0.19)	Med. Beko + Med. Mend + Med. Bord (45.6, 0.52)
F				1/4	1/4	1/4	1/4	Med. Beko (33.8, 0.0)	Med. Beko + L. Bord (50.5, 0.0)	Med. Beko + Med. Mend. + Med. Bord. (53.8, 0.0)	Med. Beko (34.2, 0.0)	Med. Beko + L. Bord (49.3, 0.03)	Med. Beko + Med. Mend + Med. Bord (52.4, 0.02)	Med. Beko (32.8, 0.0)	Med. Beko + L. Bord (45.3, 0.29)	Med. Beko + Med. Mend + Med. Bord (49.0, 0.18)
G					1/3	1/3	1/3	Med. Beko (36.0, 0.0)	Med. Beko + L. Bord (54.1, 0.0)	Med. Beko + Med. Mend. + Med. Bord. (57.2, 0.0)	Med. Beko (36.7, 0.0)	Med. Beko + L. Bord (54.2, 0.0)	Med. Beko + Med. Mend + Med. Bord (56.8, 0.0)	Med. Beko (35.5, 0.0)	Med. Beko + L. Bord (50.1, 0.0)	Med. Beko + Med. Mend + Med. Bord (53.4, 0.01)
H							1	Med. Beko (40.5, 0.0)	Med. Beko + L. Bord (60.8, 0.0)	Med. Beko + Med. Mend. + Med. Bord (63.9, 0.0)	Med. Beko (41.0, 0.0)	Med. Beko + L. Bord (61.2, 0.0)	Med. Beko + Med. Mend. + Med. Bord (63.6, 0.0)	Med. Beko (40.6, 0.0)	Med. Beko + L. Bord (59.4, 0.0)	Med. Beko + Med. Mend + Med. Bord (62.5, 0.0)

Table 5. Summary of best performing alternatives, in terms of downside, expected, and upside NPV (in 2010 US$)

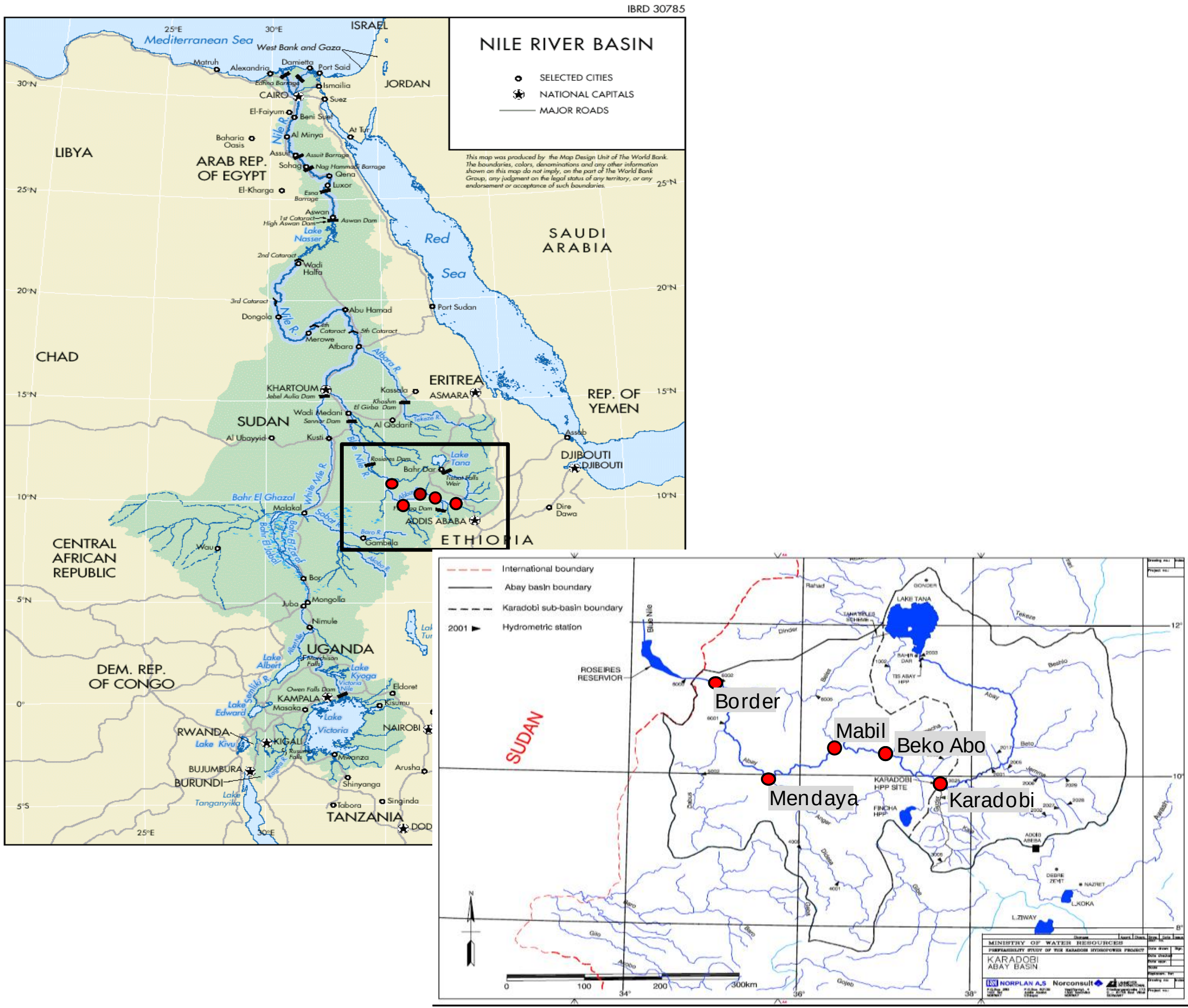
Combination	Downside NPV ($–15\_W_2$)	Expected NPV ($+0\_W_1$)	Upside NPV ($+15\_W_0$)
1-Dam	Small Beko Abo $Inf_2\_T_0\_S_1\_O_2$ 5.6 billion	Medium Beko Abo $Inf_2\_T_0\_S_2\_O_2$ 26.7 billion	Medium Beko Abo $Inf_2\_T_0\_S_2\_O_2$ 67.8 billion
2-Dams	Beko + Border (all small) $Inf_{11}\_T_0\_S_1\_O_2$ 5.8 billion	Beko + Border (all medium) $Inf_{11}\_T_0\_S_2\_O_1$ 36.1 billion	Med. Beko + Lg. Border $Inf_{11}\_T_0\_S_7\_O_1$ 105.3 billion
3-Dams	Beko + Mend + Border (all small) $Inf_{16}\_T_0\_S_1\_O_2$ 5.1 billion	Beko + Mend + Border (all medium) $Inf_{16}\_T_0\_S_2\_O_2$ 39.4 billion	Beko + Mend + Border (all medium) $Inf_{16}\_T_0\_S_2\_O_2$ 114.4 billion
4-Dams	Kar + Mab + Mend + Border (small) $Inf_{18}\_T_0\_S_1\_O_2$ -0.8 billion	Kar + Mab + Mend + Border (small) $Inf_{18}\_T_0\_S_1\_O_2$ 22.7 billion	Sm. Kar + Sm. Mab + Med. Mend + Sm. Border $Inf_{18}\_T_0\_S_{13}\_O_2$ 72.9 billion

Table 6. Summary of operating rules chosen for the "best" infrastructure, chosen on the basis of highest expected NPV

Situation	Operating Rule			Situation	Operating Rule			Situation	Operating Rule			Situation	Operating Rule		
	# of Dams				# of Dams				# of Dams				# of Dams		
	1	2	3		1	2	3		1	2	3		1	2	3
–15_W_0	O_2	O_2	O_1	–5_W_0	O_1	O_2	O_2	+5_W_0	O_1	O_1	O_1	+15_W_0	O_2	O_1	O_1
–15_W_1	O_2	O_2	O_1	–5_W_1	O_2	O_2	O_2	+5_W_1	O_1	O_2	O_1	+15_W_1	O_2	O_1	O_2
–15_W_2	O_2	O_2	O_1	–5_W_2	O_2	O_2	O_2	+5_W_2	O_2	O_1	O_2	+15_W_2	O_1	O_1	O_1
–10_W_0	O_2	O_2	O_2	+0_W_0	O_2	O_2	O_2	+10_W_0	O_2	O_1	O_1				
–10_W_1	O_2	O_2	O_1	+0_W_1	O_2	O_1	O_2	+10_W_1	O_1	O_1	O_1				
–10_W_2	O_2	O_2	O_1	+0_W_2	O_2	O_2	O_2	+10_W_2	O_2	O_2	O_1				

Note: O_1 = Hydropower maximization (25); O_2 = Coordination (38).

Figure 1. The Nile watershed.



Black lines show existing water control structures; circles show locations for proposed hydropower projects in Ethiopia (adapted from Norplan-Norconsult, 2006)

Figure 2. The highest expected NPV for each infrastructure configuration's best performing bundle: (A) Single Dam, (B) 2 Dams, (C) 3 Dams, (D) 4 Dams

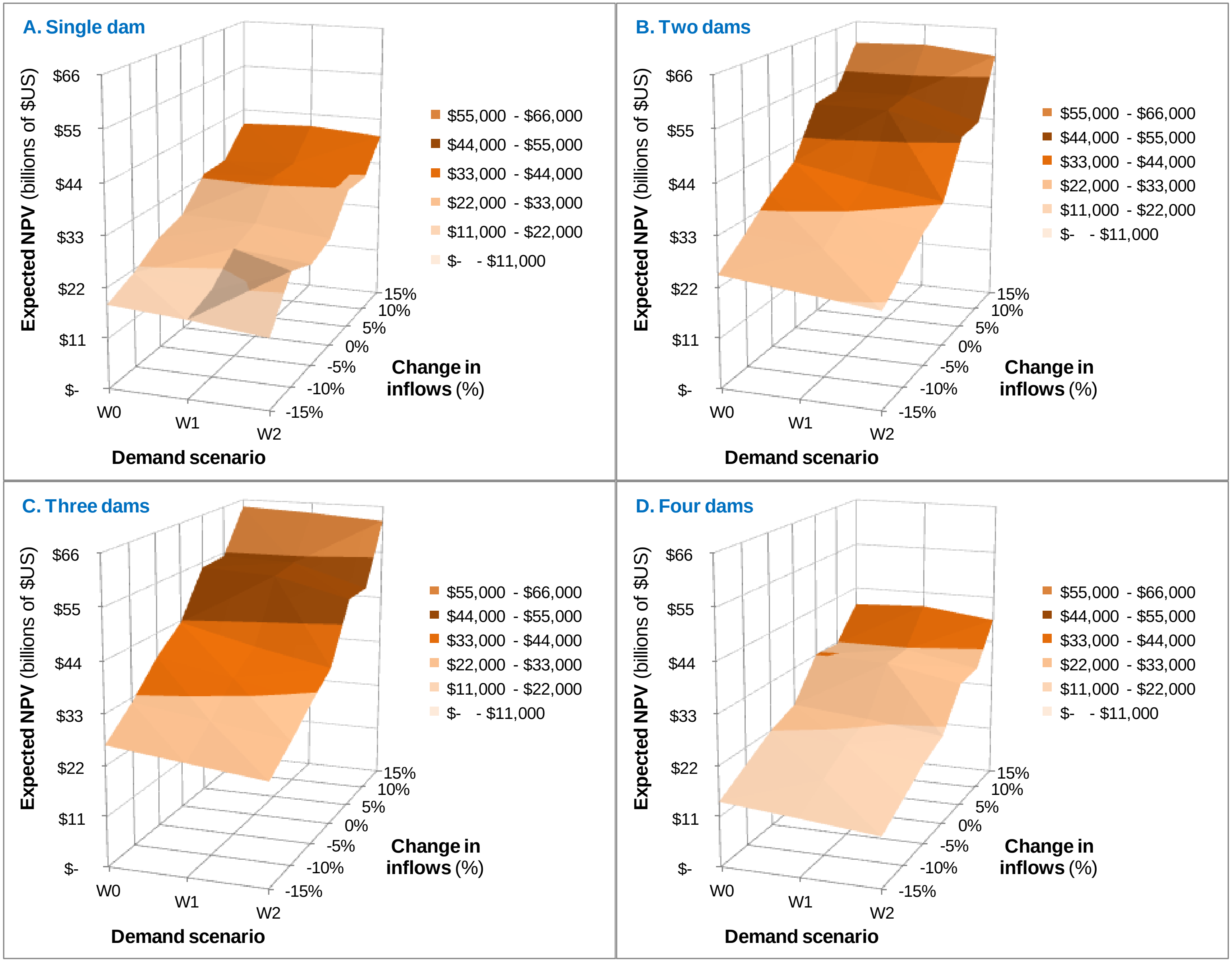


Figure 3. The relationships between risk and rewards for all infrastructure bundles evaluated in +15% inflow (top), no change in inflow (middle), and –15% inflow (bottom) climate scenarios, for the three withdrawal conditions

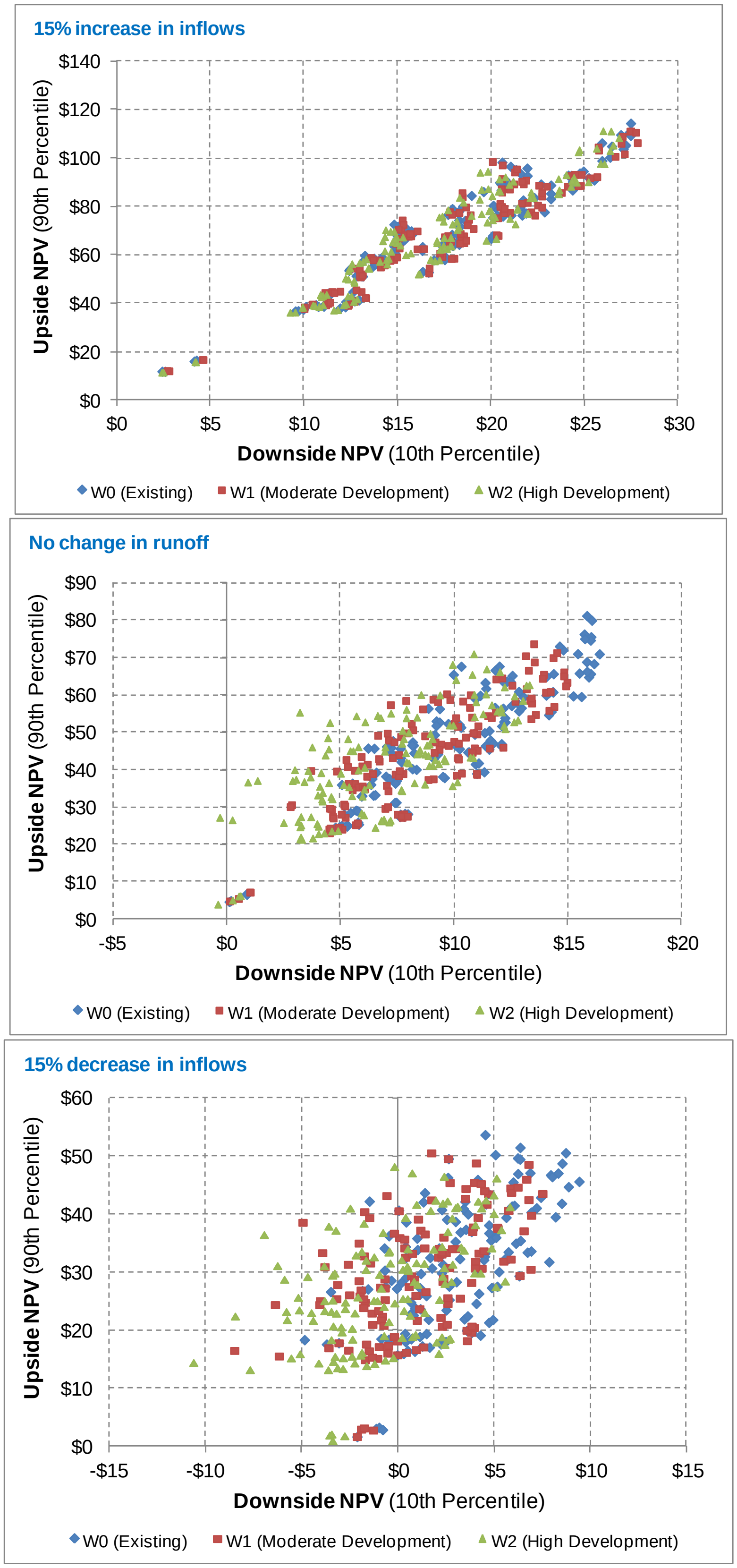


Figure 4. The relative performance metrics of the single-dam configurations across inflow scenarios, with W_0 (left) and W_2 (right) withdrawals

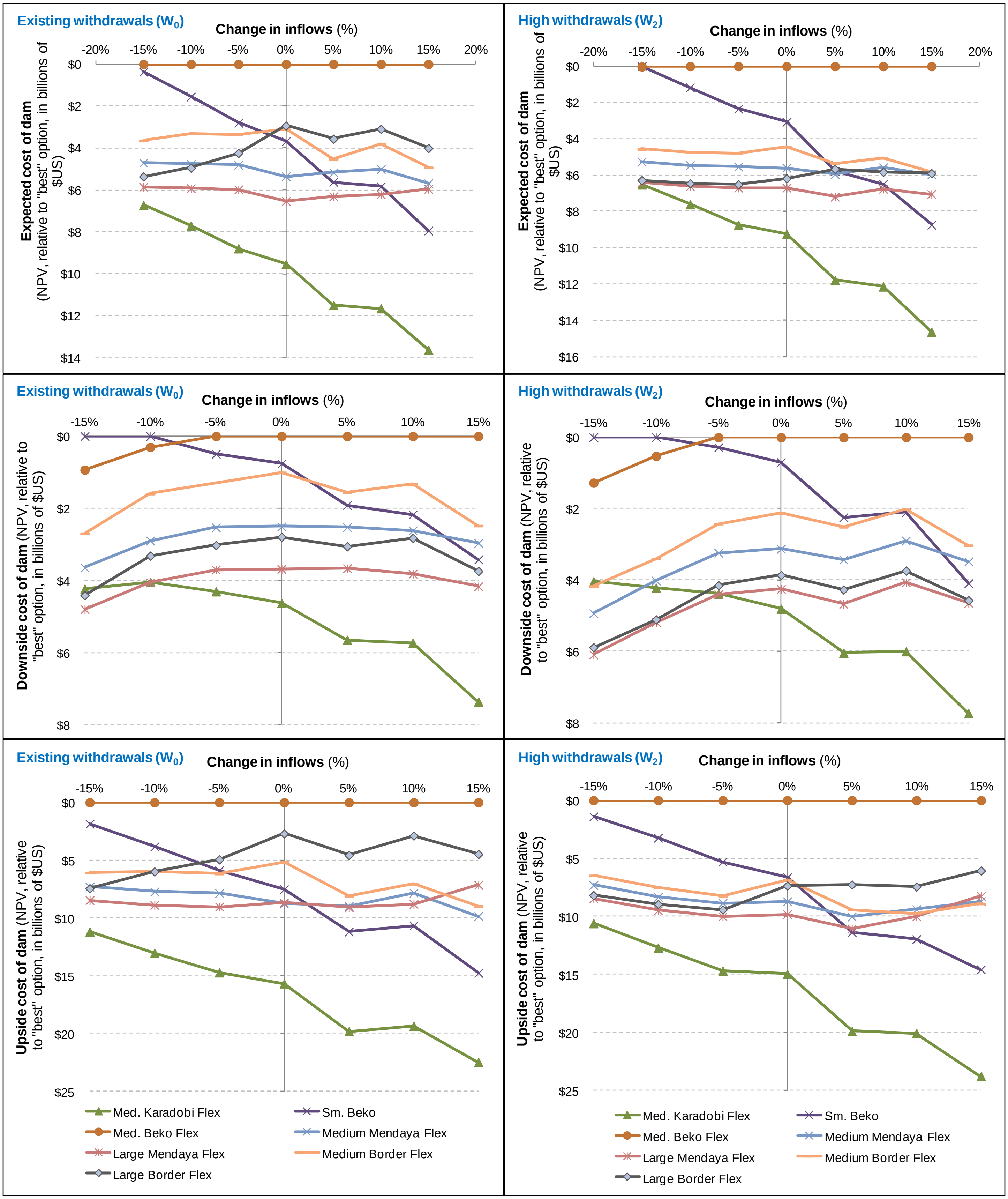


Figure 5. The relative performance metrics of the two-dam configurations across inflow scenarios, with W_0 (left) and W_2 (right) withdrawals

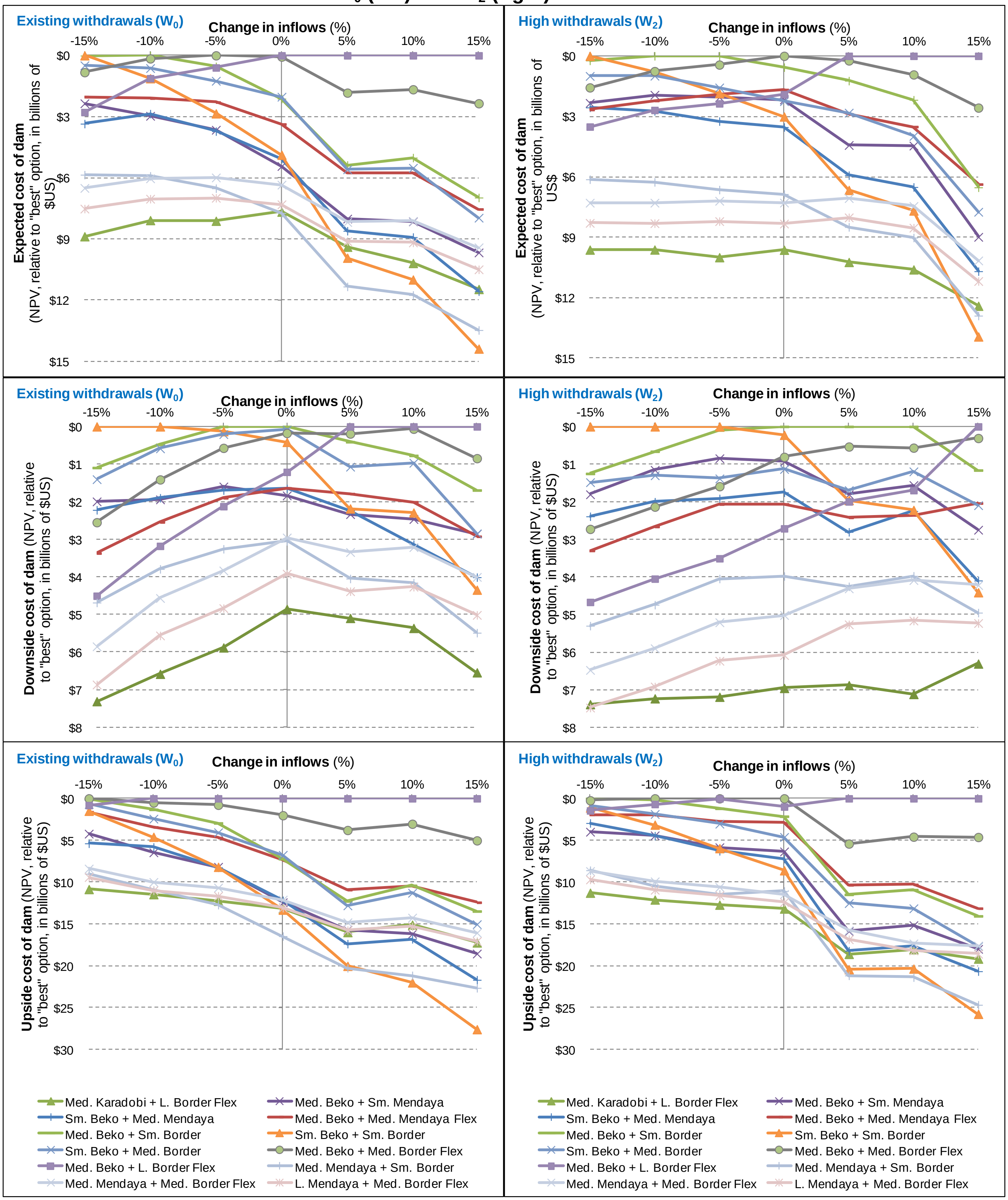


Figure 6. The relative performance metrics of the three-dam configurations across inflow scenarios, with W_0 (left) and W_2 (right) withdrawals

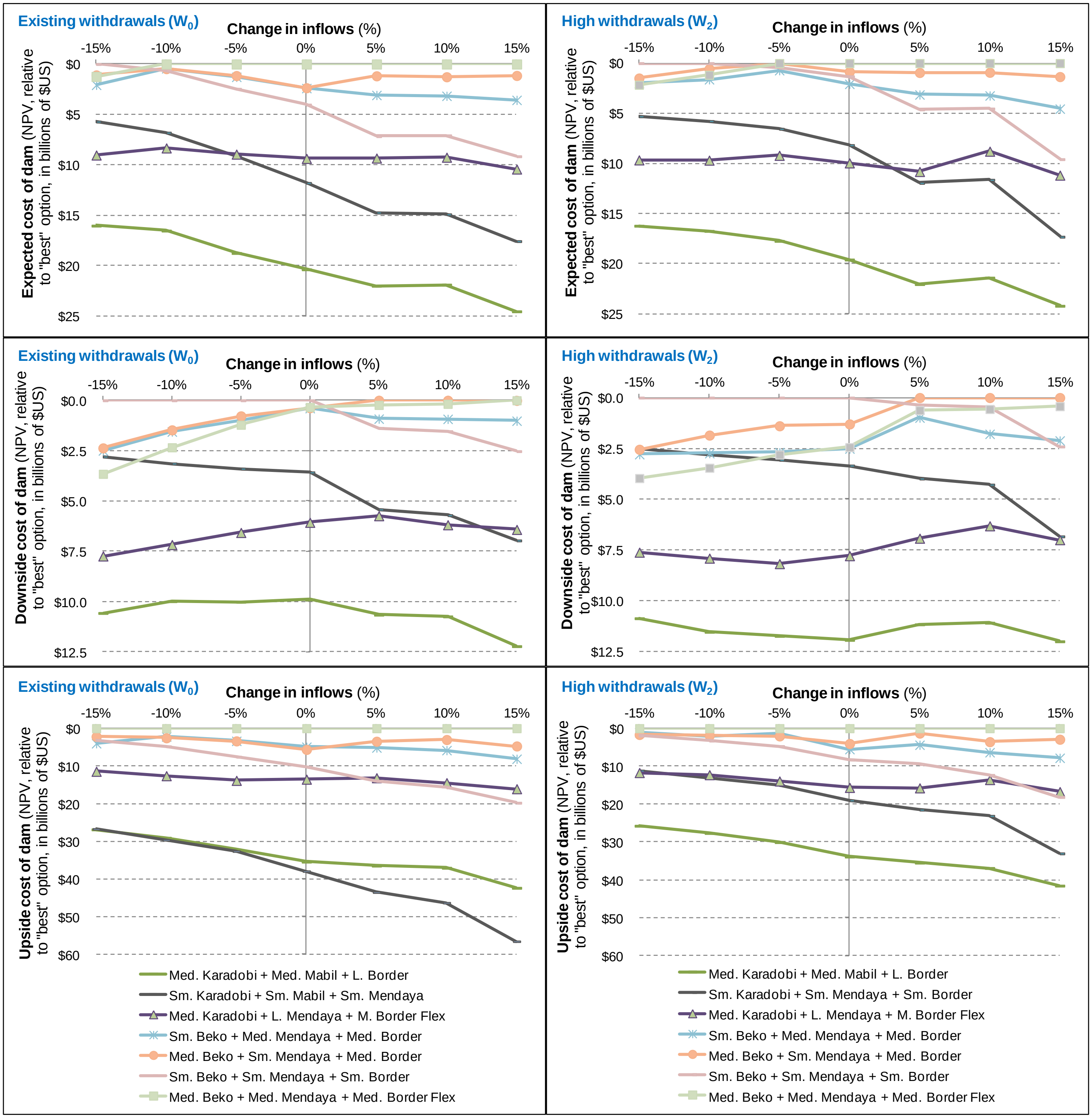


Figure 7. The cost of alternatives that include the Renaissance Dam across model conditions, in terms of expected NPV (top), lost upside (middle), and lost downside (bottom)

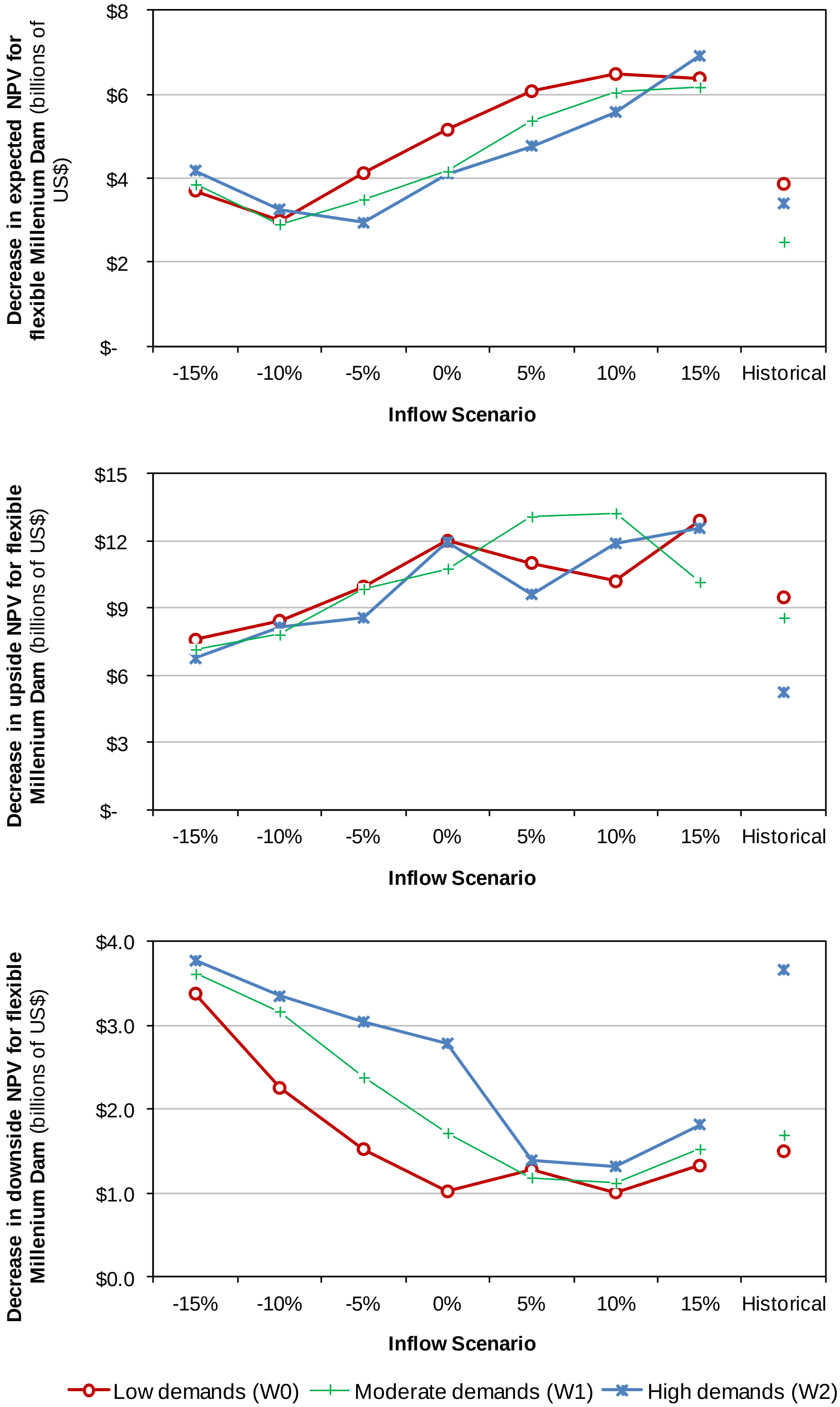
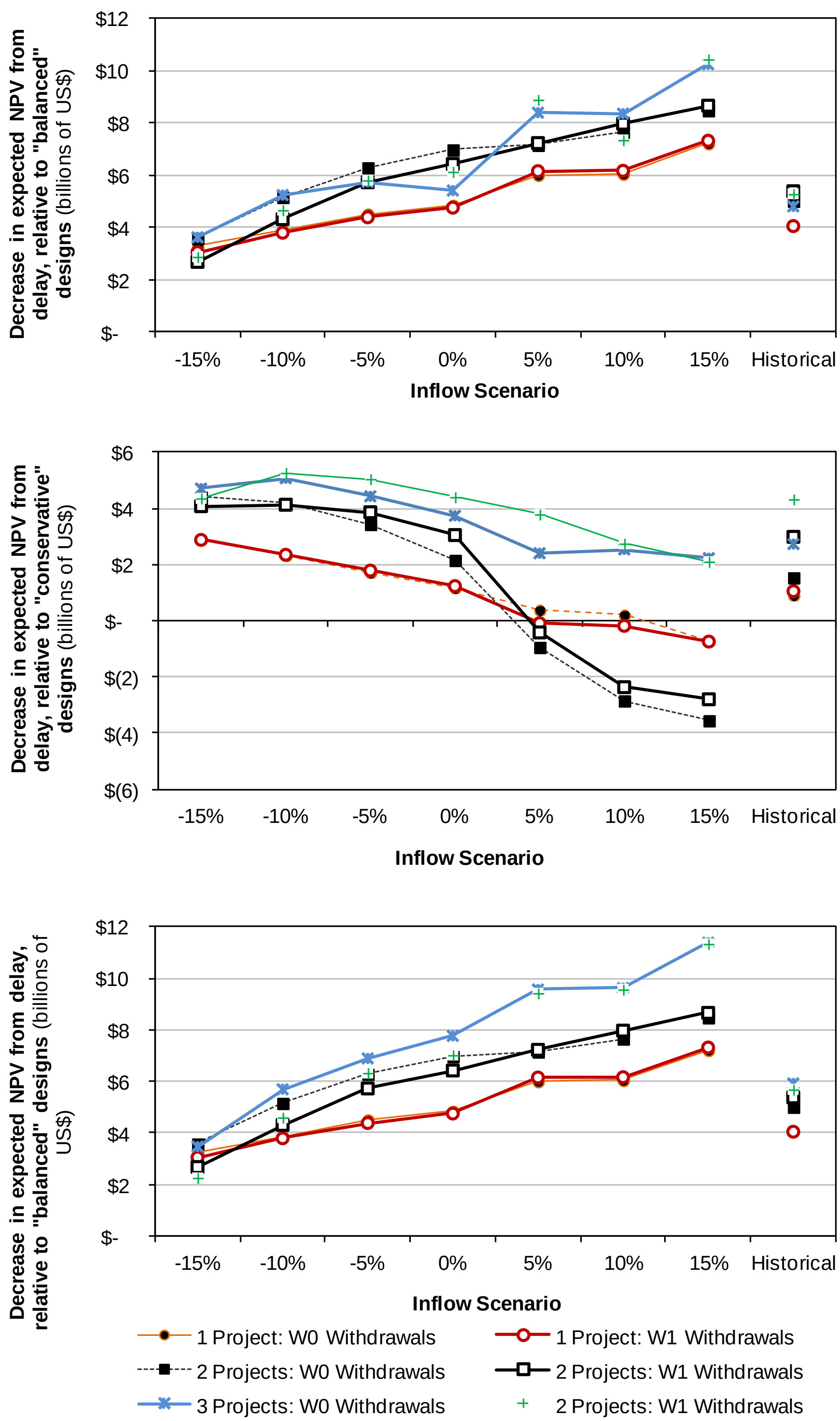


Figure 8. The cost of waiting relative to balanced (top), conservative (middle), and risk-taking (bottom) strategies



Appendix: Explanation of modeling for the economic simulations

Overview of modeling framework

Large new infrastructure projects alter movements of water in water resources systems, and therefore have basin-wide effects. Thus the economic analysis of projects considered in this paper is undertaken from a basin-wide perspective, using a partial equilibrium model. This approach presents a more complete picture of the physical and economic consequences of potential projects than has been previously available in the literature. As many project outputs and downstream impacts are defined, quantified, and monetized as best is possible. The analysis also considers more carefully and systematically the extent to which these basin-wide effects are sensitive to various conditions, resulting from (1) changes in water demands; (2) new infrastructure; and (3) climate change.

The cost-benefit calculations rely on a recently developed hydro-economic modeling framework that allows the integration of climate change impacts into the problem of planning water resources infrastructure development [Jeuland, 2010]. This hydro-economic modeling framework allows specification of a variety of functional linkages between climate change, hydrology, and economic production to better elucidate the complexities and uncertainties associated with future conditions.

Water demand conditions

Blue Nile dam projects deliver outputs into a future state of the world with uncertain water demands. To illustrate how the economic valuation of the dam projects depends on future demand conditions, the costs and benefits of dams in the Blue Nile gorge are estimated by comparing the state of the world with a dam to three conditions:

The status quo (W_0): This condition approximates current water withdrawal and infrastructure conditions in the basin.

Moderate withdrawals (W_1): This condition includes new water withdrawals and planned infrastructures in the basin, and brings Sudan up to its legal allocation as specified in the 1959 Nile Waters Agreement.

High withdrawals (W_2): This condition includes additional new water withdrawals and planned infrastructures in the basin.

These conditions are summarized in Table A1, and the locations of the new water withdrawals and dams are shown on the hydrological model schematic in Figure A1. Under the status quo, it is assumed that Egypt's target release is 55.5 billion cubic meters (bcm) annually. Sudan is using about 13.9 bcm/yr (measured at point of withdrawal, and not including reservoir losses to evaporation), less than its allocation of 18.5 bcm/yr as measured at Aswan. Withdrawals in Sudan and Ethiopia both increase under W_1 conditions, as Sudan reaches its entire Nile Waters Agreement allocation (accounting for evaporative losses and the addition of two dams in Sudan at Shereiq and Dal). Under W_2 conditions, demands further increase in Ethiopia to 5.6 bcm/yr. The new irrigation demands are scattered throughout the Nile Basin. For example, all Blue Nile hydropower alternatives would be affected by the reduced flows that accompany new consumption around Lake Tana, whereas withdrawals further downstream (e.g. in the Mendaya sub-catchment, or from the Tana-Beles diversion) have no direct effect on projects such as Beko Abo and Karadobi but do affect dams further downstream. Additional withdrawals from the Sobat only have indirect effects on the Blue Nile hydropower alternatives via their contributions to reducing flows in the downstream system in Northern Sudan and Egypt.

Economic modeling

Table A2 presents a general typology of economic costs and benefits from large water projects; those omitted from the analysis are shaded in gray. This choice of impacts, previously discussed by Whittington et al. [2009], was informed by a critical reading of project pre-feasibility studies and other available data from the Eastern Nile riparians. The assumed parameter values and possible ranges for the costs and benefits are summarized in Tables A3 and A4, and model equations are presented in Table A5.

Benefits

The benefits of the proposed Blue Nile storage reservoirs are: (1) hydropower generated from the infrastructures, (2) downstream hydropower uplift due to flow regulation, (3) delivery of timely irrigation water for drought mitigation due to flow regulation, (4) flood control, (5) carbon offsets from production of carbon-neutral energy, (6) reduced desilting costs in downstream irrigation systems, and (7) decreased treatment costs for drinking water due to lower sediment loads.

The primary economic benefit of each of the Blue Nile dams is hydroelectric power. An economic appraisal of benefits thus depends in large part on the economic value of the hydropower produced. The economic value of the hydropower generated depends largely on three factors:

1. Who purchases (uses) the hydropower, i.e., which countries and which users

2. Whether the hydropower displaces alternative sources of power, or whether it is assumed to relieve supply constraints
3. Whether it is used for peak or baseload.

Economic appraisal of dams in the Blue Nile gorge thus requires careful attention to the integration of the hydropower generated from such projects into regional power markets. In the short term, the Ethiopian market (projected total demand of 2,075 MW in 2015, compared to generation from other projects estimated at 4,000 MW) cannot absorb all of the hydropower that would be generated at large Blue Nile dams. The most accessible market for this power outside of Ethiopia is in Sudan, and Khartoum could use an additional 1,350–2,000 MW of peaking power capacity by 2015. Based on alternative cost considerations, our analysis assumes that the economic value of peak power to Sudan (and Ethiopia) is US$0.20 per kilowatt-hour, and the economic value of baseload power is $0.08 per kilowatt-hour. For peaking power, these are mainly gas oil fired combined cycle gas turbine plants ($0.18–$0.22/kW-hr, based on oil prices of $80–$100/bbl). For baseload power, the best alternatives are low head, limited output hydropower projects ($0.07–$0.1/kW-hr) or HFO fired diesel plants ($0.15/kW-hr) [PB Power Data Book, 2003].

In order to use a hydropower facility to generate peak power, the water downstream of the facility must be "re-regulated" in order to minimize erosion damages from high water releases. A second dam is thus required to even out (or "re-regulate") extreme intra-day variations in water releases. This second re-regulation dam adds to the construction costs of a peaking power project. In the Blue Nile gorge, such an option already exists at Roseires in Sudan. The Border site in Ethiopia is only about 130 kilometers upstream from the Roseires Dam, and will only be a few kilometers from the southern end of the reservoir behind the heightened Roseires Dam. The Roseires Dam in Sudan can thus re-regulate releases from dams built at Border so that they can generate peak power. Hydropower from new dams is valued assuming that 22.5% (range 20%–-25%) of power produced would be used for peaking purposes.

Average hydropower production, assumed to be for baseload, at other system dams would likely increase with Blue Nile storage due to greater flow regulation, though short term production might decrease during reservoir filling. As with the changes in demands met, the time series of incremental hydropower added to the system – both at the new infrastructures and downstream dams (hydropower at some downstream sites might also be reduced) – are taken from the hydrological simulation model output for input to the economic model.1 The reservoir filling period was thus automatically included. The real economic value of this power is allowed to change over time, especially with climate change (range 0 to +1.5% /yr with climate change, and –0.5 to 0.5%/yr without), implying a range in energy values spanning US$0.03 to US$0.27 by the end of 75 years. The justification for a higher increase in the value of hydropower under climate change is based on reasoning that conventional, fossil-fuel-intensive processes will become more costly as climate change mitigation measures are taken. Carbon offsets from hydropower are estimated using the carbon offset factor for Egypt (0.52; range 0.3 to 0.6). These are also allowed to increase in value over time (0 to +1.5%/yr).

The economic benefits of timely water delivery to downstream agriculture – mostly in Sudan – due to new projects are valued at US$0.05/m3 (range 0 to $0.10), which is consistent with older estimates of the value of Nile water to Egyptian irrigation [Molden, 1997; Perry, 1996; Wichelns, 1999]. Expert opinion based on global values in river basins where water is scarce also suggests these values are reasonable [D. Blackmore, personal communication]. The value of these reduced deficits is allowed to change over time to reflect the tightening or easing of water scarcity, depending on the climate scenario (range –0.5 to +0.5% /yr with climate change and greater water availability; +0.5 to +1.5% /yr with climate change and lesser water availability; and 0 to 1%/yr without climate change). The expected value of reduced flood risk is estimated based on existing studies to be $262 million (range $48–$447, which is multiplied by anticipated damages for a typical flood event [Cawood & Associates, 2005; Riverside and UNESCO-CWR, 2010]. The change in flood risks due to changes in Blue Nile hydrology is assumed to be directly proportional to the reduction in peak monthly flows calculated from the hydrological simulation model.

Large dams in the Blue Nile would also trap sediment, providing a variety of benefits: (1) increase the longevity of the smaller reservoirs on the Blue Nile in Sudan and possibly allow for beneficial changes in their operating rules to increase hydropower production [Jeuland, 2009; Mohamed, 2009]; (2) reduce de-silting costs in irrigation schemes such as the Gezira and in Sudanese dams; (3) reduce drinking water treatment costs (for chemical flocculants that increase sedimentation) during the flood season in Khartoum and other cities [Ahmed, 2005; Joy, 2007]; and (4) improve the potential of Blue Nile fisheries, because very few fish survive the high

[1] It should be mentioned that operating rules at all downstream reservoirs were kept the same. Uplift may therefore be underestimated, because lower silt loads downstream would almost certainly allow for implementation of more favorable operating rules at the Sudanese dams along the Blue Nile (Roseires and Sennar).

sediment and flushing operation employed in most Sudanese reservoirs during flood periods [*Hassan*, 2007]. We only include the middle two benefit categories. We assume that de-silting costs amount to US$22 million/yr (range $9–$36 million), and that the savings achieved would be proportional to the reduction in sediment loads. Water treatment costs savings are calculated in similar fashion, from an estimated annual cost of $4 million/yr (range $0.5–$6 million).

Costs

The costs included in the analysis are (1) capital investments, (2) O&M, (3) the opportunity cost of the land that is flooded by the new reservoir, (4) costs from reductions in water availability downstream due to storage in the new reservoirs (especially transient effects that may occur during the reservoir filling period), (5) resettlement for households displaced by reservoir flooding, (6) economic compensation at "replacement cost" for persons otherwise losing access to recession agriculture, (7) the cost of catastrophic risks, and (8) the cost of greenhouse gas emissions resulting from construction of the dam and flooding of the reservoir.

The proposed Blue Nile dams would require billions of dollars of capital investment, and likely take seven to ten years to construct. Capital costs for the three dams were distributed according to the construction schedules and dam sizes presented in the pre-feasibility studies, and adjustments were made to the costs for other sizes based on their relative sizes (height, number of turbines required, etc.). Uncertainty ranges for total capital expenses were allowed to span from 80% to 120% of the costs predicted by the studies. Construction delays are common in large water projects, but the roller-compacted concrete dam design allows power generation to begin prior to dam completion; it was therefore estimated that operation could begin within a range of –2 to +2 years relative to the estimated dam completion time (representing a 0 to 4 year delay from the earliest possible onset of operation). For simplicity, the total project lifespan for civil works was taken to be 75 years for all infrastructures (range 30 to 100), and electrical installations were assumed to need replacement every 40 years. This large range for the longevity of civil works stems from the very large dead storage in the potential Blue Nile dams relative to estimates of sedimentation loads in the Blue Nile; however smaller dams by themselves, which our analysis finds not to be the most attractive projects anyway, would likely have shorter lifespans.[2] Annual operation and maintenance costs were assumed to be 15% of annualized capital costs (range 10 to 20%).

The other significant capital cost consideration has to do with the inclusion of transmission costs from Roseires to Egypt, which must be included because electricity markets in Ethiopia, and Sudan, can only absorb a small amount of the hydropower that would be produced. The cost of transmission infrastructures for carrying electricity to demand markets was estimated based on estimates presented in the Eastern Nile Power Trade study [EDF and Scott Wilson, 2008], and scaled according to transmission capacity requirements [Bates, 2010]. The interconnection cost may be overestimated as other power trade projects have been moving ahead in the Nile Basin, but the 80% to 120% range of capital costs applied above should allow for potential cost savings.

For Karadobi, the Norplan study includes estimates of land costs as US$10 million. This cost corresponds only to the construction zone for the dam itself or to the entire flood zone of the new reservoir, and likely represents a lower bound for the land cost. However, there is little other productive activity in the Blue Nile canyon, and few ecological or recreational assets have been identified at this time. For purposes of this analysis, it is therefore assumed that this cost could vary from $10 million to $20 million.

Any irrigation deficits that might be induced by the new projects are determined using the outputs of the hydrological simulation model for the Nile. Incremental deficits added to downstream demand nodes by new projects in the system are calculated in the hydrological model and read into the economic model. For example, if the simulated demand deficits in year x in the downstream system increased from y bcm to z bcm as a result of dam operation, the costs associated with the $z - y$ bcm increase in deficits are attributed to the new dam.[3] The real value of these deficits is then valued at US$0.1/m^3 (range 0–$0.20), more than the value of water because

[2] It should be noted that sedimentation rates are often underestimated by a factor of 3 or more. For a recent example from Ethiopia, the reader is referred to the study by Devi et al. [2008], which discusses the Gilgel Gibe hydropower project. The storage reservoir in question was expected to last 70 years at project conception but this timeframe has now been revised to 24 years based on the first 12 years of operational data.

[3] On the other hand, if the relative magnitude of downstream deficits decreases after dam construction (as often occurs in Sudan due to more regular year-round Blue Nile flow), this water delivery is counted as a benefit.

of the loss of both irrigation rents and of other inputs invested in producing them, and these values are allowed to increase over time just as do reduced shortfalls.[4]

The Blue Nile gorge, unlike the Ethiopian highlands, is malarial, warm and humid, and sparsely populated; numbers of displaced households are estimated to be quite low for these projects. The cost for each resettled household is assumed to be ten (range 5 to 15) times the average GDP per capita in Ethiopia (US$350) based on estimates of the costs of displacement taken from a cross-country comparison of rehabilitation costs from a variety of locations around the world [Cernea, 1999]. The numbers of resettled households are allowed to range between half and two times the estimates cited in the studies (+100 to allow for the possibility of some displacement from Karadobi, given study estimates of zero affected households). A number of farmers and herders also rely on the annual Blue Nile flood for recessional irrigation and pasture land as seasonal water levels drop. For example, the Mendaya documents estimate that some 10,000 hectares are exploited in this way in Sudan and Ethiopia, and yield total economic rents of US$1.5 million, with grazing occurring on another 15,000 hectares (for an annual economic value of $1 million) [EDF, 2007a]. Costs for households losing access to these land-based livelihood activities are assumed to be $20/hectare-yr (range $10 to $100), based on "replacement cost" considerations. This base case value corresponds to an estimate of the cost of small pumping schemes; the upper bound of the range more closely approximates the annual value of agricultural products typically grown on one hectare in the zone. Like the estimates of households to be resettled, the areas lost for these activities were obtained from the pre-feasibility studies (+/- 50%).

Though seismic risks in the Blue Nile basin are low, the risk of a catastrophic failure is included as a random shock that can occur in any year with a probability of 0.01% (range 0.002 to 0.02%), or 1 in every 10,000 dam-years. In the event of a failure in year *x*, an estimate of the economic cost of failure is imposed in year *x*. This cost of failure is calculated by summing the cost of total reconstruction of the dam with the benefits lost during the period of reconstruction. This is of course a lower bound, because catastrophic damages from downstream flooding are

[4] This modeled divergence between the relative value of added versus reduced deficits is admittedly ad hoc, and the weight applied for adjustment is entirely our own. Unfortunately, we know of no data on the real cost of water deficits in the Nile Basin, and this is in any case likely to vary by location, depending on the fertility of soils, agricultural practices, and labor markets. There is clearly a need for such information from the Nile countries. It is also true that some deficits could probably be anticipated, especially in Egypt; thus the extent of the inputs lost is uncertain.

not included. In the base case analysis, catastrophic risks are included as an expected cost, i.e., the probability of failure in any given year multiplied by the cost of failure.

Finally, the project studies included estimates of natural carbon releases and construction emissions for the three projects. For natural releases due to a project, it was assumed that the decomposition of biomass would occur during construction, i.e., as land is cleared, and that none of the lost biomass would replace alternative fuel sources in the region (ranging from 0 to 100% replacement of alternative sources).[5] These natural emissions are also assumed to be proportional to flooded area for different reservoir sizes, and are allowed to vary by +/- 1 million tons of CO_2 equivalent. Construction emissions are assumed to be distributed proportionally to the capital outlays for construction, are adjusted according to the volume of concrete in the dam, and are allowed to vary by +/- 50% of the cited values in the studies. Emissions are valued at US$20/ton of emitted carbon (range US$10 to $30).

Omissions

A number of impacts listed in Table A2 are not included, and these omissions deserve mention. First, there are no plans to use the reservoirs for irrigation or municipal water supply near the dam sites given the topography and low population density; thus changes in irrigation, municipal and industrial water use are not considered. In addition, the implications for recreation, navigation, fisheries, and public health arising from the projects are not included, because the Blue Nile canyon is not densely populated and these effects are expected to be small. Nonetheless, as there have been no thorough studies of these effects, a more complete assessment is warranted. In terms of public health effects, Blue Nile dams may encourage settlement along the shores of the reservoir, which could lead to increased incidence of water-related diseases such as malaria and schistosomiasis.

Some other costs and benefits of flow regularization in the Blue Nile may be substantial, but data are lacking to evaluate them properly: (1) changes in sediment loads in the system (only some such effects are included), and (2) changes in ecosystem services from the Nile flood other than the recessional agriculture and grazing described above. Preliminary environmental impact assessments of the dam sites did not identify critical negative ecological or habitat loss issues associated with these locations, but these may not have been sufficient [*EDF*, 2007a; b; *Norplan-Norconsult*, 2006]. Also, secondary and economy-wide impacts – including enhanced regional

[5] This will overstate costs in the sense that decomposition will not occur as soon as land is cleared.

economic integration, peace and cooperation, and general development impacts – are not included; these include some of the "multiplier" effects that can be difficult to attribute to specific projects [*Bhatia et al.*, 2005; *Boardman et al.*, 2005]. Such benefits have been mentioned in the Nile development literature, but predicting them would require additional research, methodological innovations, and general equilibrium tools; these were judged to be beyond the scope of our research.

The discount rate

With these caveats in mind, we turn to the issue of aggregating costs and benefits over time (discounting). Since these are large public investments, we use a social discount rate of 4% (range 2% to 6%), which is consistent with that suggested by most economists, and among those writing specifically about climate change [*Jeuland*, 2010]. The range of 2% to 6% is, however, not a good estimate of the opportunity cost of capital, especially if Ethiopia decides to finance the Renaissance Dam or other subsequent projects from domestic sources. Without external financing, the opportunity cost of forgone development projects in Ethiopia could be very high.

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Table A1. Water demand and infrastructure conditions for increased development

Indicator	Units	W_0	W_1	W_2
Target withdrawals for irrigation				
Ethiopia	bcm/yr	0.3 bcm	2.9 bcm (+2.6)	5.6 bcm (+5.3)
Sudan		13.9 bcm	16.4 bcm (+2.5)	16.4 bcm (+2.5)
Egypt		55.5 bcm	55.5 bcm (+0.0)	55.5 bcm (+0.0)
New dams				
Ethiopia	n.a.	n.a.	None	None
Sudan			Shereiq and Dal	Shereiq and Dal
Egypt			None	None

Figure A1. Water demand and infrastructure locations in the Nile model

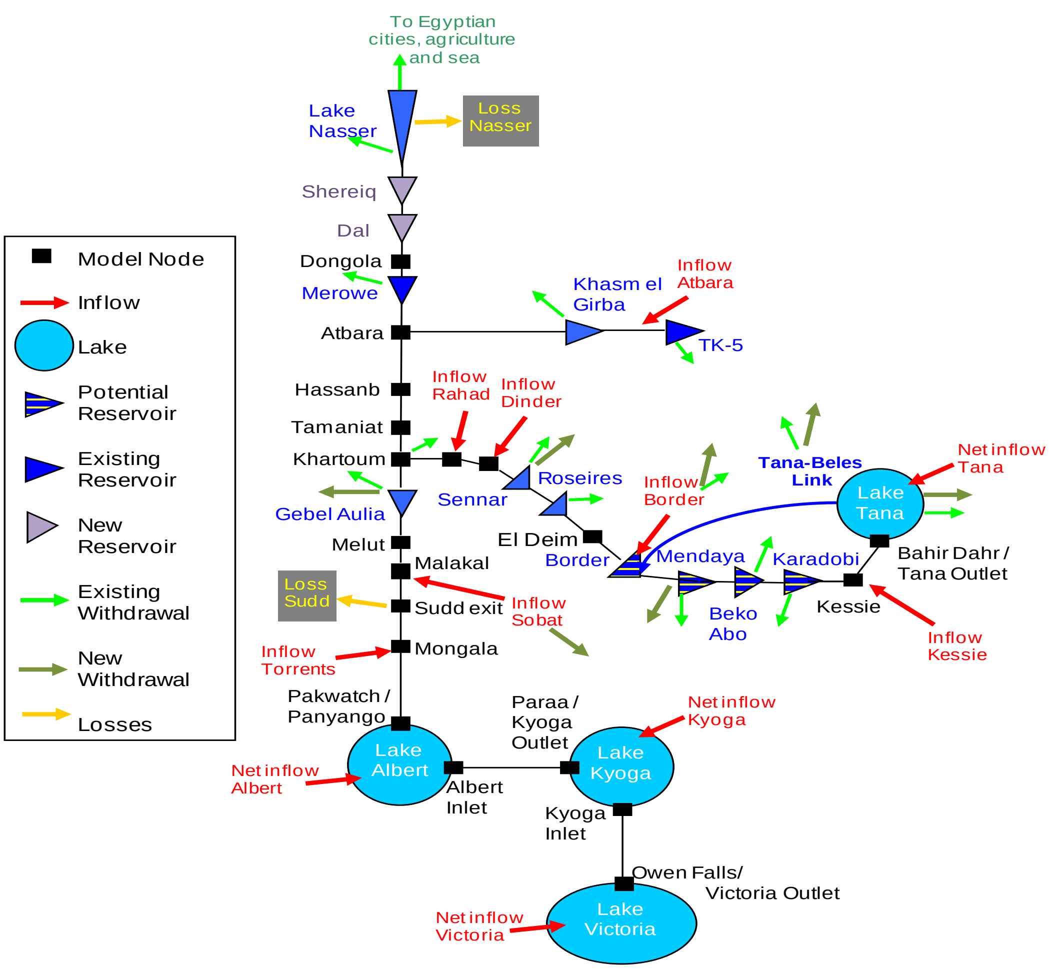

Table A2. Benefits and costs of large water projects,

adapted from *Whittington et al.* [2009]

Benefits	**Costs**
Hydropower generation at dam site	Capital investment (dam, energy transmission infrastructure, land, etc.)
Downstream hydropower uplift	Operation and maintenance
Improvements in downstream availability / timing of water supply for irrigation or other uses	Declines in downstream availability / timing of water supply for irrigation or other uses (including filling costs)
Flood control	Additional opportunity cost of flooded land
Carbon offsets	Resettlement for flooded households
Reduced desilting costs in downstream irrigation systems (Gezira)	Carbon emissions (construction, reservoir clearing)
Decreased costs of treatment for drinking water due to lower sediment concentration	Loss of recessional agriculture
Improvements in fisheries	Catastrophic risk
Improvements in navigation	Reduced viability of brickmaking in Sudan

Table A3. Parameter assumptions for costs and benefits that vary across infrastructure alternatives

(uncertainty ranges in brackets)

	Symbol	Karadobi	Beko Abo	Mabil	Mendaya	Border
General parameters						
Dam construction time (yrs)	t^c	Sm: 6 Med: 7	Sm: 6 Med: 7	Sm: 5 Med: 6	Sm: 6 Med: 7 Lg: 10	Sm: 6 Med: 7 Lg: 10
Installed capacity (MW)		Sm: 1,600 Med: 2,000	Sm: 2,000 Med: 2,500	Sm: 1,200 Med: 1,600	Sm: 2,000 Med: 2,400 Lg: 2,800	Sm: 1,600 Med: 3,000 Lg: 5,250
Full supply level (masl)		Sm: 1,100 Med: 1,142	Sm: 1,030 Med: 1,065	Sm: 880 Med: 900	Sm: 741 Med: 800 Lg: 830	Sm: 580 Med: 610 Lg: 640
Cost parameters[b]						
Capital cost of dam (billions of US$)	C^{dam}	Sm: 2.1 [1.7–2.5] Med: 2.7 [2.2–3.2]	Sm: 2.5 [2.0–3.0] Med: 3.5 [2.8–4.2]	Sm: 2.2 [1.8–2.6] Med: 2.8 [2.3–3.3]	Sm: 2.3 [1.9–2.7] Med: 3.4 [2.7–4.1] Lg: 4.3 [3.4–5.2]	Sm: 2.2 [1.8–2.6] Med: 3.8 [3.0–4.6] Lg: 5.2 [4.1–6.3]
Capital cost of transmission lines (billions of US$)[c]	$C^{transmission}$	Sm: 0.6 [0.5–0.7] Med: 0.7 [0.5–0.9]	Sm: 0.7 [0.5–0.9] Med: 0.9 [0.7–1.1]	Sm: 0.7 [0.5–0.9] Med: 0.9 [0.7–1.1]	Sm: 0.7 [0.5–0.9] Med: 0.8 [0.6–1.0] Lg: 1.0 [0.8–1.2]	Sm: 0.6 [0.5–0.7] Med: 1.0 [0.8–1.2] Lg: 1.1 [0.9–1.3]
# Households displaced (‘000s)	n	0.1 [0.0–0.2]	0.1 [0.0–0.2]	0.1 [0.0–0.2]	0.1 [0.0–0.2]	Sm: 2.8 [1.4–5.7] Med: 4.2 [2.1–6.3] Lg: 6.5 [3.2–9.8]
Area of downstream grazing/recession agriculture production lost: (‘000 hA)	A^{lost}	25 [12.5–37.5]	25 [12.5–37.5]	25 [12.5–37.5]	25 [12.5–37.5]	30 [15–45]
Project emissions (millions of tons of CO_2)	E	Sm: 3.5 [2.0–5.0] Med: 4.7 [3.1–6.3]	Sm: 3.1 [1.6–4.6] Med: 4.7 [3.0–6.4]	Sm: 2.0 [0.6–3.4] Med: 2.8 [1.3–4.3]	Sm: 3.9 [2.3–5.4] Med: 6.8 [5.0–8.6] Lg: 10.6 [8.7–12.5]	Sm: 3.7 [2.3–5.0] Med: 5.7 [4.1–7.3] Lg: 8.8 [6.8–10.8]
Benefit parameters						
Percentage of peak power generation	p^{peak}	22.5 [20–25]	22.5 [20–25]	22.5 [20–25]	22.5 [20–25]	22.5 [20–25]
Reduction in sediment flow to Sudan (%)	Δs	60 [5–25]	65 [10–30]	65 [10–30]	70 [40–60]	75 [45–65]
Hydropower generated at dam (GW-hr/yr)	$H_t^{BlueNile}$	Time series obtained from hydrological simulation model	Time series obtained from hydrological simulation model	Time series obtained from hydrological simulation model	Time series obtained from hydrological simulation model	Time series obtained from hydrological simulation model
Net gain in hydropower in Sudan and Egypt (GW-hr/yr)	$H_t^{Egypt+Sudan}$					
Change in timely irrigation water downstream (bcm/yr)	I_t^d					
Decrease in probability of flood (%)	λ_t					

Notes: Cost estimates for different sizes were adjusted based on relative dam size (for capital costs), capital costs (for emissions) or reservoir area (for displaced households). These include cost of transmission to the grid in Ethiopia (480 km from Karadobi, 300 km from Mendaya and 380 km from Border) and to the Sudanese grid at Kosti [*Norplan-Norconsult*, 2006; *EDF*, 2007a; 2007b]. All costs in 2011 $US.

Table A4. Parameter assumptions that are the same across alternatives

(uncertainty ranges in brackets)

Description	Symbol	Parameter value	
General parameters			
Dam project duration (yrs)	D	75	[30–100]
Discount rate (%)	r	4	[2–6]
Cost parameters			
Construction delay (yrs)	d	0	[(–2) – 2]
Renewal of electrical infrastructures (yrs)	t^{elec}	40	[No range]
O&M expenditures (As % of annualized capital cost)	$P^{O\&M}$	15	[10–20]
Opportunity cost of land (millions of US$)	C^{land}	10	[10–20]
Cost of additional deficits (US$/cubic meter)	$C^{deficits}$	0.1	[0–0.2]
Economic loss per displaced household (US$)	$C^{resettlement\ per\ HH}$	3,500	[1,750–5,250]
Economic replacement cost per hectare (US$)	$C^{lost\ land}$	20	[10–100]
Risk of catastrophic failure (%)	μ	0.01	[0.002–0.02]
Benefit parameters			
Value of baseload power (US cents/kW-hr)	v^{hb}	8.5	[7–10]
Value of peak power (US cents/kW-hr)	v^{hp}	20	[18–22]
Net value of timely water downstream (US cents/m^3)	v^{i}	5	[0–10]
Expected flood damage in Sudan (millions of US$/yr) [a]	F	262	[48-477]
Price of offsets (US$/ton CO2)	$v^{offsets}$	20	[10–30]
Carbon offset factor	ε	0.52	[0.3–0.6]
Fraction of Gezira O&M for desilting	p^{s}	0.9	[0.75–1.0]
Annual Gezira O&M cost (millions of US$/yr)	OM^{Gezira}_{t}	25	[10–40]
Annual sediment control cost for Khartoum drinking water (millions of US$/yr)	OM^{dw}_{t}	4	[0.5–6]
Change parameters: Historical (%/yr, net of inflation)			
Value of hydropower	Δv_h	0	[(–0.5)–0.5]
Value of timely water	Δv_i	0.5	[0–1]
Change parameters: Climate change (%/yr, net of inflation)			
Value of hydropower	Δv_h	0.5	[0–1.5]
Value of timely water [b]	Δv_i	0–1	[(–0.5)–1.5]
Value of offsets	Δv_O	0.5	[0–1.5]

[a] Average of two estimates commissioned by the Eastern Nile Technical Regional Office that include damages to buildings; very high estimates have been adjusted downwards [*Cawood & Associates*, 2005; *Riverside and UNESCO-CWR*, 2010]].

[b] For scenarios with increasing inflows, it was assumed that the value of timely water is 0%/yr (range -0.5 to +0.5); for scenarios with decreasing inflows or no change, the value increases 1%/yr (range 0.5 to 1.5).

Table A5. Equations included in the partial equilibrium model for assessing the costs and benefits of large water storage facilities in the Blue Nile gorge[a]

Description	Equation
Discounting factor in year t	$\delta_t = 1 / (1 + r)^{t-1}$ for $t = 1,\ldots,D$
Benefits	
Total value of hydropower (millions of US$ in year *t*)	$V^{hydro}_t = (H^{BlueNile}_t + H^{Egypt+Sudan}_t) \cdot [v^{hp} \cdot p^{peak} + v^{hb} \cdot (1 - p^{peak})] \cdot (1 + \Delta v^h)^{t-8}$
Net value of irrigation (millions of US$ in year *t*)	$V^{irrigation}_t = (I^d_t \cdot v^i) \cdot (1 + \Delta v^i)^{t-8} \cdot 10^3$ if $I^d_t > 0$ $V^{irrigation}_t = (I^d_t \cdot v^i \cdot C^{deficits}) \cdot (1 + \Delta v^i)^{t-8} \cdot 10^3$, otherwise
Value of flood control (millions of US$ in year *t*)	$V^{Flood}_t = F \cdot \lambda_t$
Value of carbon offsets (millions of US$ in year *t*)	$V^{carbon}_t = (H^{BlueNile}_t + H^{Egyp+Sudan}_t) \cdot v^{offsets} \cdot \varepsilon \cdot (1 + \Delta v^O)^{t-8} / 10^6$
Value of sediment control (millions of US$ in year *t*)	$V^{sed}_t = \Delta s \cdot (p^s \cdot OM^{Gezira}_t + OM^{dw}_t)$
Total benefits	$B = \Sigma_t[\delta_{t+d} \cdot (V^{hydro}_t + V^{irrigation}_t + V^{flood}_t + V^{carbon}_t)]$
Costs	
Capital cost (millions of US$ in year *t*)	$C^{capital}_t = [\eta^c_1 \cdot (C^{dam} + C^{transmission})] + C^{land}$ if $t = 1$ $C^{capital}_t = [\eta^c_t \cdot (C^{dam} + C^{transmission})]$ if $1 < t < t^c$ $C^{capital}_t = C^{elec}$ if $t = t^{elec}$
Resettlement and economic rehabilitation (millions of US$)	$C^{resettlement}_t = n \cdot C^{resettlement\ per\ HH} + A^{lost} \cdot C^{lost\ land}$ if $t = 1$ $C^{resettlement}_t = A^{lost} \cdot C^{lost\ land}$, otherwise
Operation and maintenance cost (US$ in year *t*)	$C^{O\&M}_t = p^{O\&M} \cdot (C^{dam} + C^{transmission}) / D$ if $t > 7$ $C^{O\&M}_t = 0$, otherwise
Cost of carbon emissions from flooding + construction (millions of US$ in year *t*)	$C^{Carbon}_{,t} = \eta^c_t \cdot E \cdot v^{offsets}$
Cost of catastrophic risk (millions of US$ in year *t*)	$C^{damfailure}_t = \mu \cdot$ (Cost of reconstructing dam + lost benefits)
Total costs	$C = \Sigma_t[\delta_t \cdot (C^{capital}_t + C^{O\&M}_t + C^{resettlement}_t + C^{carbon}_{,t} + C^{damfailure}_t]$[b]

Note: $\eta_{c,t}$ is a generic function that indicates the proportion of capital costs incurred in year *t* (taken from the project-specific schedule of capital expenses). Because the incremental outputs due to the projects are taken directly from the hydrological simulation model, the benefit calculations account for the time lag stemming from reservoir construction and filling.

[a] Variable definitions are shown in Tables A3 and A4.

[b] Losses to infrastructure and livelihoods downstream from a catastrophic dam failure are not included due to lack of data.