Water Resources Planning under Climate Change: Assessing the Robustness of Real Options for the Blue Nile

Marc Jeuland[1,‡], Dale Whittington[2,3]

[1] Sanford School of Public Policy and Duke Global Health Institute; Durham, NC; USA
[2] Departments of Environmental Sciences & Engineering and City & Regional Planning, UNC-Chapel Hill; Chapel Hill, NC; USA
[3] Manchester Business School, Manchester; UK
‡ Corresponding author:
Email: marc.jeuland@duke.edu
Address: Rubenstein Hall 188; Box 90239; Durham, NC, 27708; USA
Telephone: +1-919-613-4395

Key points:

1. No planning alternative is likely to dominate across plausible future conditions
2. We present a method for generating information for the selection of robust planning alternatives
3. Downside and upside metrics can assist enhanced decision making

Abstract

This article presents a methodology for planning new water resources infrastructure investments and operating strategies in a world of climate change uncertainty. It combines a real options (e.g., options to defer, expand, contract, abandon, switch use, or otherwise alter a capital investment) approach with principles drawn from robust decision-making (RDM). RDM comprises a class of methods that are used to identify investment strategies that perform relatively well, compared to the alternatives, across a wide range of plausible future scenarios. Our proposed framework relies on a simulation model that includes linkages between climate change and system hydrology, combined with sensitivity analyses that explore how economic outcomes of investments in new dams vary with forecasts of changing runoff and other uncertainties. To demonstrate the framework, we consider the case of new multipurpose dams along the Blue Nile in Ethiopia. We model flexibility in design and operating decisions – the selection, sizing, and sequencing of new dams, and reservoir operating rules. Results show that there is no single investment plan that performs best across a range of plausible future runoff conditions. The decision-analytic framework is then 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 should arise. The approach could be extended to explore design and operating features of development and adaptation projects other than dams.

Keywords: Real options, robust decision-making, Monte Carlo simulation, dams, climate adaptation, Nile Basin, Ethiopia

1. Introduction

The planning of large water resources infrastructures and other similarly long-lived development projects is fraught with uncertainty. The demographic and economic changes that are anticipated to occur over a span of decades influence the types of water investments that are thought to be needed, as well as how and when such investments should be constructed [*Maass et al.*, 1962]. Such infrastructure will be built over a planning period during which the effects of climate change will unfold, and planners are now forced to confront the challenges arising from predictions about climate change and its potential effects on hydrological systems. Numerous researchers have speculated about the implications of such combined socio-economic and climatic changes for water resources availability and management over the coming century [*Alcamo et al.*, 2007; *Arnell*, 2004; *Vorosmarty et al.*, 2000]. There is widespread consensus that new, improved planning methods are needed to address such deep uncertainty.

Water resources planning models typically require the planner to assign *ex ante* probabilities to possible future states of the world in order to identify optimal or near-optimal solutions, usually expressed in terms of expected outcomes. In practice, though, it may be difficult to determine or justify such probabilities [*Hobbs et al.*, 1997; *Lempert and Groves*, 2010]. In such circumstances, if no single infrastructure or management strategy dominates others across a range of plausible future conditions, it becomes difficult to provide compelling guidance on what should be done. In this paper we offer evidence that such non-dominance can easily occur in real-world water resources infrastructure planning problems, based on a specific application to hydropower investments in the Blue Nile. We suspect that such non-dominance is probably the norm rather than the exception, given the deep uncertainties affecting the economics of long-lived investments in an era of climate change.

Faced with this reality of deep uncertainty over the planning horizon, we develop and demonstrate a different modeling approach for water resources infrastructure planning. The approach combines certain principles of *robust decision-making* (RDM) with simulation of the economic performance of infrastructures characterized by a range of *real options* (definitions for italicized terms follow and appear in the supplemental lexicon attached to this article). We consider *real options* to be features of infrastructure or managerial systems that allow *recourse*, that is, changes in the physical configuration or operations of infrastructure facilities to respond effectively to conditions that vary over time (e.g., options to defer, expand, contract, abandon, switch use, or otherwise alter a capital investment) [*De Weck et al.*, 2004; *Maqsood et al.*, 2005; *Trigeorgis*, 1996; *Wang and de Neufville*, 2006]. These options may arise from the inherent operational flexibility associated with different infrastructure designs, or from the possibility of delay or modification of investments until a time when more or better information on performance is obtained [*Steinschneider and Brown*, 2012]. In most other planning approaches, the value of such adaptation options is assessed using risk-based methods in which specific assumptions are made about the probabilities of future states of the world.

RDM refers to a class of methods that are used to identify robust strategies, or strategies that perform relatively well, compared to the alternatives, across a wide range of plausible future states of the world [*Groves and Lempert*, 2007]. In this paper we present a combined approach that can help decision-makers better understand how the simulated economic outcomes for a potential new *planning alternative* (e.g., a specific combination of design features and operating rules, also referred to as an *alternative* for brevity) vary across a set of plausible future *scenarios*. Here and elsewhere, we use the term *scenario* to describe a unique combination of runoff and water demand conditions. This definition of "scenario" could be generalized to a larger set of "deep" uncertainties (e.g. social, political, environmental) for which well-specified probabilities may not exist [*Knight*, 1921]. We consider climate and development uncertainties because they are a current focus of attention among scholars [*Dessai and Hulme*, 2007; *Morgan et al.*, 1999]. In many regions, for example, the predictions of climate models do not agree in terms of changes in precipitation, even within a single emissions trajectory. Similarly, predictions of the evolution of water demands over a long time horizon have often been spectacularly inaccurate [*Gleick*, 1998].

We do not try to determine 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 plausible future scenarios; and (2) we believe that neither decision makers nor planners are likely to be satisfied with optimal choices that follow from assignment of essentially arbitrary probabilities to future changes in hydrology and anticipated water demands. Even more flexible optimization methodologies -- such as stochastic optimization, robust stochastic programming, robust optimization, or sampling stochastic dynamic programming -- suffer from such limitations [*Mulvey et al.*, 1995; *Sahinidis*, 2004; *Sen and*

Higle, 1999; *Vicuna et al.*, 2010]. Indeed, it makes little sense to speak of optimal alternatives if optimality depends on what is assumed about a highly uncertain future.

Instead, our approach begins with enumeration of the sources of uncertainty inherent in the planning problem, and then partitions these uncertainties according to whether they are best characterized as "probabilistic risk" or "deep uncertainty." Next, the ranges for both probabilistic risks and deep uncertainty) and the distributions for probabilistic risks are specified; deep uncertainties are modeled as unique and separate scenarios within which the probabilistic risks apply. The approach then uses Monte Carlo simulation, applied within a specific future scenario, to produce the *downside risk* (10th percentile of the cumulative distribution of simulated Net Present Value (NPV)), *expected value* (mean of the NPV distribution), and *upside potential* (90th percentile of the NPV distribution) of alternatives comprised of different design features [*Cardin et al.*, 2007; *Dixit and Pindyck*, 1994]. Finally, rather than further aggregating these performance indicators for a particular alternative by assigning probabilistic weights to the plausible scenarios [*Brekke et al.*, 2009; *Hobbs et al.*, 1997], the indicators are transformed into relative measures of downside, expected, and upside performance that facilitate comparisons across the "deep" uncertainty scenarios using RDM principles. This transformation is achieved by normalizing the aforementioned indicators for all alternatives, by the values of the highest-performing alternative in a particular scenario.

The fact that we attempt to incorporate non-probabilistic uncertainties into our decision framework in this way, using scenarios, does not resolve the basic problem of deep uncertainty. By definition, such uncertainty cannot be fully anticipated and planned for, and cannot be represented in the choice of modeled scenarios. In addition, as we will show, applying this combined RDM and real options approach will not yield a simple decision rule when deep uncertainties rule out the possibility of a dominant alternative across modeled scenarios. Nonetheless, application of the decision framework does provide information on the tradeoffs between upside potential (and expected value) and downside risk, within and across a variety of possible future conditions. This tradeoff is important because some decision makers may be risk averse and especially concerned about downside outcomes [*Harou et al.*, 2009], while others may play a high stakes game that maximizes upside returns [*Whittington et al.*, 2014].

The next section describes this combined real options and RDM-based decision-analytic framework in more detail, and how it can be applied to water resources planning problems. Section 3 presents the Blue Nile application. It begins with a summary of the hydropolitical context, and then describes the specific models and assumptions of the analysis, including the definition of scenarios. We then explain the alternative designs included in our analysis. Section 4 reports the case study results. In Section 5 we discuss the implications of the analyses and offer some more general observations.

2. Evaluation framework: Combining real options and RDM methods

The process of planning large-scale water resources investments has long been conceptualized to be a staged problem in which the ability to revise or amend initial decisions (i.e., recourse) plays an important role [*Erlenkotter et al.*, 1989; *Howe*, 1971; *Maqsood et al.*, 2005]. Some of the decisions made during this process allow greater flexibility to respond to future uncertainties than others. For example, initial location and design decisions will influence the potential for modification of reservoir filling rates (in the short term) and long-term operation. The analytical framework presented below is developed to accommodate the adaptive flexibility provided by such real options [*Gill*, 2013], while also enabling comparisons of the economic value of water resources plans that contain different combinations of design (e.g., infrastructure selection, sequencing, sizing) and operational features (e.g. water release rules). We next present the mathematical framework that underpins our analysis and specify a set of metrics that are used for comparing the outcomes of different planning alternatives.

We begin by assuming that a given alternative can be considered *ex ante* to produce a distribution of potential economic outcomes, as measured by the net present value (NPV) of the system-wide incremental changes it generates within a water resources system (e.g., in hydropower produced, or irrigation water demands met), relative to the counterfactual system without that infrastructure. This NPV distribution results from a well-characterized set of uncertainties that can be specified in probabilistic terms. In our example application this set includes all parameters contributing to costs and benefits other than system water demands and runoff conditions (see Supporting Information for details). Importantly, to obtain these NPV distributions, deep uncertainties must be assumed away; in other words, the distributions of outcomes are generated under a specific set of circumstances (e.g., a specific climate or water demand regime). Using Monte Carlo methods, analysts take repeated random draws from well-specified distributions of the uncertain parameters that contribute to economic outcomes [*Whittington et al.*, 2012]. If every parameter contributing to NPV were deemed to be subject to deep uncertainty (i.e., no probability distributions could be specified), Monte Carlo simulation would become impossible, and relative comparisons would have to be guided purely by principles of RDM.

Following the generation of NPV outcome distributions, real options analyses typically focus on indicators of the performance of different investment paths, specifically measures of downside, average, and upside value [*Dixit and Pindyck*, 1994]. These indicators apply to a planning alternative j in a given (assumed) *planning scenario i*. These scenarios correspond to plausible states of the world that are characterized by deep uncertainties, or that cannot be expressed in probabilistic terms (for example, our application considers climate and water demand conditions to be of this nature). We focus on the following indicators (all for scenario i):

1. Downside risk ($D_{j,i}$): The 10th percentile of the NPV distribution for alternative j;
2. Expected value ($NPV_{exp,j,i}$): The mean of the NPV distribution for alternative j; and
3. Upside potential ($U_{j,i}$): The 90th percentile of the NPV distribution for alternative j.

As will be demonstrated further below in the results, risk-reward differences or tradeoffs within a given scenarios i can be shown graphically by plotting $D_{j,i}$ against $U_{j,i}$. For example, such plots may reveal that selection of a small dam is a conservative, high $D_{j,i}$ alternative, but that it implies lower $U_{j,i}$ under current climate and demand conditions, whereas a large dam may be a risk-taking alternative characterized by low $D_{j,i}$ and high $U_{j,i}$. Also, the specific percentiles defined above for downside (10th) and upside (90th) could be considered somewhat arbitrary. Therefore, we suggest testing the sensitivity of results to alternative definitions as these indicators.

There are three main reasons why these indicators do not allow easy comparison across planning alternatives. First, multiple alternatives may perform well but not dominate one another across all three indicators, such that other kinds of comparisons become necessary in order to understand their relative value. Second, economic outcomes for a set of infrastructure projects that are operated in a specific way do not account for recourse or flexibility. Third, and perhaps most importantly, is the problem of comparing the performance of alternatives across scenarios for which probabilities cannot be assigned because of the presence of deep uncertainties. The first two of these problems can readily be handled using real options theory, whereas the third cannot, which motivates our use of principles from RDM.

To address these challenges, we first define relative performance metrics for each planning alternative *j*, that measure its performance in comparison with that of the highest-performing alternative in scenario *i* (which may not be the same across the three metrics). Relative performance helps to characterize the "regret," or departure from highest performance, associated with a particular infrastructure choice [*Lempert and Groves*, 2010]. These relative metrics enable quantification of the relative costs, measured at three points in the NPV distribution, of selecting alternative *j* if the conditions in scenario *i* are realized:

$$OC_{j,\mathrm{i}} = NPV_{\mathrm{exp},i}{}^{*} - NPV_{\mathrm{exp,j,i}}; \tag{1}$$

$$RR_{j,i} = D_{\mathrm{i}}{}^{*} - D_{j,i}; \tag{2}$$

$$RU_{j,i} = U_i^* - U_{j,i}; \text{ where} \qquad (3)$$

$OC_{j,i}$ = expected opportunity cost of alternative *j* in scenario *i*;
$NPV_{\exp,i}^*$ = expected NPV of the alternative with the highest expected NPV in scenario *i*;
$RD_{j,i}$ = relative downside NPV lost by alternative *j* relative to the alternative with the highest downside NPV in scenario *i*;
D_i^* = downside NPV of the alternative with the highest downside NPV in scenario *i*;
$RU_{j,i}$ = relative upside NPV lost by alternative *j* relative to the alternative with the highest upside NPV in scenario *i*;
U_i^* = upside NPV of the alternative with the highest upside NPV in scenario *i*.

Next, we modify the metrics to incorporate flexibility; i.e. $OC_{j,i}$ is replaced with the expected opportunity cost $OC_{flex,j,i}$ of alternative *j* in scenario *i*:

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

This amount $OC_{flex,j,i}$ accounts for the fact that the performance of an alternative *j* can be modified by recourse, or by exercising real options to modify that alternative, in the future. The cost $\chi_{k,j}$ is the extra initial investment required to allow flexible conversion of alternative *j* into alternative *k*; this may correspond to the cost of construction of multiple intake levels that allow adjustment of operations, the cost of construction that allows subsequent enlargement of an infrastructure, or investment in adaptive management capacity to efficiently modify operating rules. The minimization operator indicates that the true opportunity cost of alternative *j* in scenario *i* is the cost that is lowest after accounting for this possibility of adjustment of the alternative, accounting for the cost of that flexibility.

These calculations allow us to assess whether $OC_{\text{flex}j,i} < OC_{j,i}$ for each scenario i, such that alternative j with flexibility becomes relatively more attractive than the nonflexible alternative j. The relative upside and downside for each alternative j and situation i can be adjusted in similar fashion. The only extra computational effort needed is to store the values of NPV costs $\chi_{k,j}$ associated with that flexibility, and to use these to adjust the relative metrics as shown in equation 4

Still, the problem of comparing alternatives across scenarios (characterized by deep uncertainty) remains. To address this issue, we first turn to principles of RDM, which aim to identify alternatives that meet a "satisficing" criterion, that is, that perform adequately (in relative terms, or with respect to meeting specific benchmarks) across a wide variety of conditions [*Lempert and Groves*, 2010]. To guide these comparisons, we define three investment strategies (note that the definition of these strategies is not a part of RDM, which rather provides a framework for comparing among them). These three strategies correspond to specific investment alternatives (or groups of alternatives) that would be selected using decision rules that focus on a different portion of the distribution of potential outcomes. The *conservative strategy* corresponds to the alternative with the highest downside NPV in the worst case scenario. This is the planning alternative that would be selected using a traditional maximin criterion from decision theory, because it seeks to maximize worst case NPV. For each alternative j, we first identify the scenario i that produces the lowest $D_{j,i}$, and then define the worst case as the scenario that appears most often across the set of alternatives. The conservative strategy then corresponds to $\max(D_{j,worst})$. The *risk-taking strategy* – selected using a maximax criterion – corresponds to the alternative that generates the highest upside NPV in the best case scenario. For each alternative *j*, we first identify the scenario *i* that produces the highest $U_{j,i}$, and then define the best case as the scenario that appears most often. The risk-taking strategy then corresponds to the alternative favored by $\max(U_{j,best})$. Finally, we define a *balanced strategy* as the set of alternatives that is not dominated by (e.g., not inferior to) these conservative and risk-taking strategies, considering outcomes across all potential scenarios and the three relative performance metrics.

We compare these three investment strategies using graphical representations of their economic performance in terms of the relative metrics for downside, expected, and upside NPV cost derived above, accounting for flexibility. It should be emphasized that we stop short in this paper of suggesting which of these three strategies – conservative, balanced, or risk-taking – should be selected, and which of the metrics should be applied. We believe that choice should depend on decision makers' relative tolerance for risk (reflected in the choice of metrics), and additionally, on their tolerance for ambiguity or willingness to ascribe more or less weight on specific scenario representations of the deep uncertainties (reflected in the choice of scenarios to consider). In this sense, we deviate from the RDM approaches implemented in the literature, which still aim to select investment alternatives on the basis of specific satisficing criteria.

In addition, one way to maintain flexibility in the design of investments may be to wait, since "deep" uncertainty may be partially resolved over time [*Arrow and Fisher*, 1974]. Using the modeling framework developed above, one can test the hypothesis that delay combined with enhanced information could be justified economically. We emphasize that much additional work analyzing the value of information could be done. Finally, as will be shown further below using the example of the Grand Renaissance Dam from the Blue Nile, one can evaluate the value of specific development paths that may already have been chosen, for example, favoring irrigation over hydropower generation, or making an investment decision to construct a particular infrastructure.

3. The Nile Application

3.1. Hydro-political context of the Eastern Nile

The idea of storing Nile waters in the Blue Nile gorge in Ethiopia has long been on the minds of Nile Basin peoples, and the first comprehensive plans for multi-purpose dam development were developed over 50 years ago [*Erlikh*, 2002; *USBR*, 1964]. 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. Until recently, political, technical, and financing obstacles had prevented such projects from being implemented. However, early in 2011 Ethiopia announced that it would build the "Grand Renaissance Dam" (sometimes called the "Millennium Dam") at a site near the Ethiopia-Sudan border. This site is near a previously discussed site for a smaller dam termed the "Border Dam" in various plans.

Several recent trends and events appear to have contributed to Ethiopia's decision to initiate this construction project. In the past, Egypt occupied a position of geopolitical and economic strength relative to other Nile countries [*Waterbury*, 2002]. Egyptians have long feared that their water rights could be compromised by upstream actions such as dam building, especially in Ethiopia, where most of the Nile flow originates. 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 engaged in wide ranging discussions on establishing just such a cooperative framework agreement. At the same time, international consultants working for the Ethiopian Ministry of Water Resources prepared detailed feasibility studies for several of the most promising Blue Nile dam sites, studies which directly contributed to much greater understanding of how different upstream development projects could affect the Nile river system [*BCEOM et al.*, 1998; *EDF*, 2007a; b; *Norplan-Norconsult*, 2006].

The multilateral discussions of the NBI reached an impasse over the downstream riparians' request for explicit acknowledgment of "current uses and rights" to Nile waters in 2009. By this time the hydropolitical balance among Nile riparians had begun to shift. Ethiopia and other Nile riparians increasingly have the capacity to marshal the financial resources needed to proceed unilaterally with the construction of large dams costing several billion dollars [*McCartney and Girma*, 2012; *McDonald et al.*, 2009]. In addition, the political dynamics in the basin, particularly recent events in Egypt, have altered the balance of power in the basin.

Ethiopian leaders also now argue that Blue Nile dams such as the Grand Renaissance Dam will deliver benefits to both Sudan and Egypt, even in the absence of formal cooperation. 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 such projects has not been fully characterized [*Blackmore and Whittington*, 2009; *Block and Strzepek*, 2010; *Tilmant and Kinzelbach*, 2012; *Whittington et al.*, 2005]. One of the objectives of this paper is thus to offer a basin-wide economic assessment of investment options for dams on the Blue Nile in Ethiopia over a wide range of plausible future conditions. Our analysis first considers the largest infrastructure choice set, unconstrained by Ethiopia's decision to construct the Grand Renaissance Dam. We utilize our analytical framework to calculate the economic consequences (in terms of the relative performance metrics presented in Section 2) that result from initial selection of the Grand Renaissance Dam.

The Nile Basin is an interesting location for application of our approach for several reasons. First, as discussed above, there are numerous attractive sites in the Blue Nile for large new multipurpose dams. Second, there is a growing sense that upstream regulation in this river may generate system-wide, multipurpose benefits [*Blackmore and Whittington*, 2009]. Third, there is great uncertainty concerning how climate change will affect the Nile basin, and limited work on how this uncertainty plays into the economic attractiveness of potential Blue Nile dams [*Block and Strzepek*, 2010; *Conway and Hulme*, 1996; *Sayed and Nour*, 2006]. New or existing infrastructures may play an important role in adaptation to climate change, but little empirical research exists to guide planners as to which water resources development paths provide the greatest adaptation benefits.

3.2. Characterizing deep uncertainties: Climate and water demand scenarios

Although climate uncertainty provides much of the motivation for our approach, the contribution of this paper is not to generate state-of-the-art temperature and hydrological runoff projections from climate change models [*IPCC*, 2007; *Leavesley*, 1999; *Wood et al.*, 1997; *World Bank*, 2009]. We also do not focus on the innovative scenario generation procedures that others have proposed [*Laurent and Cai*, 2007]. Instead, our analysis explores the sensitivity of the economic benefits of multipurpose dams to average increased temperatures consistent with climate projections for this region in the year 2050, which range between 2 and 3°C across basin locations [*Strzepek and McCluskey*, 2007], as well as to changing precipitation, with associated linkages to runoff, evaporation, and irrigated crop water requirements. Much of the motivation for this approach stems from previous findings that the economic benefits of hydropower dams in the Blue Nile are highly sensitive to changes in runoff [*Jeuland*, 2010].

More specifically, each planning alternative is evaluated from a basin-wide perspective for seven hydrological scenarios, ranging from mean reductions of 15% to increases of 15% over historical conditions, in increments of 5% (labeled by the % change in runoff: -15, -10, -5, 0, +5, +10, +15), and three assumptions about consumptive water withdrawals by Egypt, Sudan, and Ethiopia (labeled W_0, W_1, or W_2), which together yield 3 x 7 = 21 scenarios (Table 1). No specific probabilities are assumed for these scenarios; they are modeled independently.

This range of changes in runoff is informed by the available precipitation projections for the Nile Basin (summarized in Table 2) combined with a runoff sensitivity analysis using prior rainfall-runoff modeling and dry, average and wet model results for the A2 emissions trajectory of the AR4 report [*Strzepek and McCluskey*, 2007].

We highlight two important assumptions underlying the way we model these changes. First, they are spatially invariant, i.e., we apply these changes to inflows (from runoff) into the Nile system. Second, because we rely on an existing model for generating stochastic flows, we assume that mean changes in runoff and temperature are time-invariant, i.e. we perturb flows but maintain stationarity. We acknowledge that these simplifications limit the accuracy of our climate change results, but we do not believe they prevent illustration of our methodology because non-stationarity, spatially differentiated projections, and innovative scenario generation techniques could be readily incorporated into the analysis with additional work (as discussed further below).

For specifying the magnitude and locations of additional water withdrawals that accompany our three demand scenarios – current withdrawals (W_0), moderate (W_1) and high (W_2) development – we rely on information from country Master Plans (see Supporting Information for details). These increased water withdrawals thus have varying impacts on the economics of reservoirs situated at different locations in the basin: some new withdrawals are upstream of some or all of the new reservoir sites and directly reduce hydropower generation. Others are located downstream of some or all dams and only affect the economics of new upstream projects indirectly, via their downstream interaction with the modified hydrology accompanying those new dams.

3.3. The Nile models

Our modeling framework consists of three linked models for stochastic runoff generation, hydrological routing, and Monte Carlo simulation of economic outcomes for different hydropower dam alternatives located at five Blue Nile sites. Below we describe the basic structure of the models; the Supporting Information includes further explanation of costs and benefits, assumed ranges for uncertain model parameters, and other model details. The hydrological components are run using a monthly time step, while the economic model aggregates annual costs and benefits into the NPV outcome indicators. These models contain explicit linkages between climate change and runoff, system hydrology and production, and valuation of economic outputs.

The hydrological analysis for a particular climate scenario begins with the generation of ten thousand years of stochastic monthly inflows into the system, accounting for the spatial and short-term temporal correlation present in the historical flow data for the system (the stochasticity of temperature is not considered). The stochastic flow generation model has an autoregressive form; the selection of normal or lognormal distributional assumptions and the number of lags (from 1 to 3 months) vary by inflow node based on the patterns detected in the historical time series' available [*Jeuland*, 2009]. Cumulative frequency distributions of generated flows in the absence of mean changes in runoff show very close agreement with the historical frequency distributions, though autocorrelation of flows across years is underestimated. To produce flows for the runoff scenarios, the mean flows in all months are altered by the same constant percentage change corresponding to that particular scenario.

These ten thousand years of monthly inflows are then divided into 100-year sequences, each of which is run through the hydrological routing model once for each planning alternative. The hydrological model thus yields one hundred unique 100-year sequences of monthly physical system-level outputs (e.g., hydropower produced, water demands met, monthly flow amounts) for each alternative, in each scenario. The economic model then uses Monte Carlo simulation to randomly select from these 100 possible sequences of physical system outputs and from probability distributions of the other uncertain risk-based parameters (including factors like the infrastructure lifespan, value of hydropower, and change in the relative value of hydropower over time). In this way, the simulation incorporates both natural hydrological variability, as reflected in the 100 flow sequences, and economic uncertainty, yielding a single NPV outcome in each Monte Carlo trial.

For the sake of brevity, we refer to a Monte Carlo analysis of economic outcomes for a single alternative in a specific water withdrawal and climate scenario using the hydro-economic simulation model as an *analysis*. Our analyses consist of 5000 Monte Carlo trials, and use the 5000 outcomes to produce a distribution of NPV outcomes for each alternative-scenario combination.

3.4. The planning alternatives and real options

Our analysis includes multipurpose dams located at five sites along the Blue Nile for which pre-feasibility or other identification studies have been completed – Karadobi, Beko Abo, Mabil, Mendaya, and Border (Figure 1). The proposed sites have different relative advantages. Because flow is higher at downstream sites, a dam at Border could provide the most regulation and water release through hydropower turbines. However, siltation loads would be higher, reducing project lifespan, and net evaporation for a given reservoir area would be greater because of lower rainfall over the reservoir and higher average temperatures in the western part of the catchment. Dams situated furthest upstream (e.g., Karadobi and Beko Abo) also have the most favorable topography, and therefore highest head and lowest reservoir surface area per unit of storage, but these would also have lower inflows. The average historical flow at Karadobi, for example, is about 42% of that at Border. A mid-gorge dam (e.g., Mendaya, where flow is 71% of that at Border) would balance these tradeoffs.

Table 2 indicates the various combinations of dam features for which we simulate economic outcomes. The specific design features we include are dam configuration, sequencing, timing, and size (we also consider two types of operating rules for each combination of these dam features). The real options include the availability of sites for subsequent dams, and their sizes; these features allow for changes to be made even after a decision has been made to construct the dam, as described below. In total, we consider many combinations of dam features, which together yield a total of 350 unique planning alternatives (as listed in the Supporting Information):

1. Configuration. We model the 17 feasible dam configurations (5 individual dams, and 12 combinations). Not all configurations are feasible because some downstream dam reservoirs would flood upstream sites (for example, a dam at Beko Abo floods Karadobi). Initial location decisions thus create more or less flexibility (real options) for future configuration changes.
2. Sequencing. Our analysis mostly assumes that upstream dams would be built first, allowing subsequent projects to benefit from enhanced flow regulation. We relax this assumption when we consider the attractiveness of investment paths that begin at Border, which corresponds to the choice Ethiopia made by starting with the Grand Renaissance Dam. Sequencing is not a real option, but rather corresponds to exercising options to build in a particular order.
3. Timing. In the multi-dam combinations, we consider faster (10-year lags between operation of dams added in sequence) and slower (20-year) staging of projects. The possibility of delaying investment in a two (or more) dam cascade is a real option associated with configurations containing fewer projects.
4. Size. Based on data availability, we model three different sizes for Mendaya and Border, and two at the other sites. While small dams are relatively inflexible, larger dam sizes may be structured to contain real options, if they allow for flexibility in operations, e.g., water releases through turbine intakes located at different levels.
5. Operating rule. We incorporate two operating rules, "hydropower-based" (O_1) and "downstream coordination" (O_2). The hydropower-based rules are derived from optimized single-dam rule curves (based on target monthly elevation levels) proposed in pre-feasibility studies, which ignore the potential for multi-reservoir optimization

> of energy generation. The downstream coordination operating rule includes a trigger to force minimum releases if storage in the downstream High Aswan Dam (in Egypt) drops below 60 billion cubic meters (bcm). The ability to switch between these operating rules is a real option provided by all configurations.

Each of the 350 specific planning alternatives is a unique package of these five features. Their performance is assessed in 7,350 different Monte Carlo simulation analyses (350 alternatives x 21 scenarios). Using the metrics defined in Section 2, we are able to assess: (1) whether there may be complementarities among dams; (2) whether allowing for flexibility (e.g., recourse as made possible by real options) has a significant influence on the NPV outcomes of the alternatives; and (3) whether changes in future hydrological or water withdrawal conditions alter conclusions about which alternatives perform best. For simplicity, our presentation in this paper provides direct graphical comparisons of only the limited set of alternatives that perform best according to the relative metrics defined above.

In addition, we assume for simplicity that: (1) changes in operating rules are costless; (2) smaller dams cannot be converted into larger dams; and (3) larger dams can be flexibly 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 extra years required for building a larger project. This is clearly a lower bound on the costs of this downsizing flexibility because multiple hydropower intakes would likely be required to allow such changes.

4. Results

4.1. Alternatives with highest expected NPV, assuming known inflow probabilities

Since much of the rationale for the approach presented in this paper hinges on the hypothesis that the “best” performing alternative may vary across plausible future conditions to which probabilities cannot readily be assigned, we begin by demonstrating the sensitivity of expected NPV to the runoff and demand scenarios. To do so, we assume that inflow probabilities are known (which of course is not the case) so that we can compute a single expected NPV value for each planning alternative. We then identify which alternative has this highest expected NPV as the assumed probabilities change. We simplify the choice set by limiting this comparison to the configuration and sizing features alone.

The results in Table 4 show that the configuration of dams in the “best” expected value alternative is actually stable across inflow and withdrawal conditions, though the expected NPV varies widely. Among single dam alternatives, Beko Abo always has the highest expected NPV, though its size varies, as discussed below. Beko Abo + Border (again, with varying sizes) is the most attractive of the two-dam configurations, and the three-dam cascades always adds Mendaya to these two. The four-dam combination, which requires a small dam at Mendaya and none at Beko Abo (which is replaced by Mabil + Karadobi), is consistently dominated by the best two- and three-dam combinations (results not shown). Because this 4-dam configuration also performs poorly in terms of downside and upside NPV, we do not consider the four-dam cascade in what follows.

Despite the stability of the choice of infrastructure sites, the size of the preferred infrastructures in these best alternatives changes across inflow-withdrawal combinations. In general, combinations of smaller dams perform better when inflows are low and upstream withdrawals are high (Cases A-C in Table 4), because energy production drops and reservoir filling takes more time under these conditions. Larger infrastructures perform better under the opposite circumstances (Cases F-I), because their higher capital costs are compensated by the greater and earlier hydropower generation that comes with higher flow. This sensitivity of the dam sizing performance to scenario conditions has important implications for the phasing and sequencing of multi-dam cascades in the Blue Nile. Selection of a small dam at Beko Abo appears to make little economic sense if only a single dam will be built (appearing only in Case A with high withdrawals), yet this size appears in 9 different 3-dam combinations shown in Table 4. Similarly, the best 3-dam configurations include small or medium dams at Mendaya and Border, and not the larger designs. Since the three-dam configuration with Beko Abo, Mendaya and Border always generates the highest expected NPV, a planner might therefore opt for a smaller first investment at Beko Abo to maintain the future potential of a multi-dam investment path.

There is similar variation in the sizes of the best second and third investments. For example, large Border (i.e., the Grand Renaissance Dam) appears 12 times in the best two-dam configuration. However, this dam precludes all of the most attractive three-dam combinations because it floods Mendaya. As explored further below, two-dam alternatives that include the

Grand Renaissance Dam therefore always entail some loss of expected NPV relative to the most attractive alternatives, which contain a three-dam cascade.

4.2. The risk-reward space for the planning alternatives

Risk preferences may also influence how decisions makers' weight specific infrastructure alternatives; as such we next examine the performance of alternatives in terms of the three NPV metrics – downside, expected and upside NPV. Comparing the performance of the alternatives across the scenarios, we identify three key results. First, there are many inferior options lying below the high downside NPV and high upside NPV frontier in any given scenario (Figure 2 shows results for three runoff conditions). Second, the nature of the tradeoff between downside (risk) and upside (reward) changes dramatically across basin conditions. Third, none of the alternatives on this frontier include the Grand Renaissance Dam, which appears to have far more storage and energy-generating capacity (and therefore higher capital cost) than is needed given the Blue Nile flow at this location. These key results are not sensitive to the percentile indicators used to measure upside and downside returns.

Exploring the variation across basin conditions, we find that there is little tradeoff between risk and rewards when inflows increase by 15%. Under high flow conditions, 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 because plenty of water is available to meet multiple objectives. With no change in runoff, the tradeoff remains modest unless upstream irrigation withdrawals increase. For example, with moderate (W_1) or high (W_2) irrigation development conditions, the highest upside alternative has a downside NPV that is US$2 (or US$3) billion worse than the lowest risk alternative (in US$2011); this represents 13-25% of the highest downside NPV under these conditions. With a 15% decrease in inflows, there is a more substantial tradeoff across all three withdrawal conditions. Under status quo (W_0) withdrawals, the highest upside project is about $5 billion worse in terms of downside NPV – representing 50% of the maximum of US$10 billion for this metric – than the most conservative one, and this gap increases to more than $6 billion for W_2 conditions. Indeed, the highest upside NPV alternative has a small negative downside NPV when withdrawals are high.

4.3. Comparing planning alternatives using the RDM-real options framework

The complexity of selecting a "best" alternative increases as we consider additional features – sequencing, timing, and operating rules – and the flexibility they introduce. The results presented thus far have been limited to comparisons in terms of expected NPV (contingent on specific inflow probabilities) and to graphical displays of the risk-reward tradeoff across conditions; they do not allow for the determination of the specific bundles of features contained in the most favorable alternatives. In Table 5, we present the details of these best alternatives, as defined by the greatest possible downside NPV across scenarios (i.e., the lowest flow (-15%), highest demand (W_2), $–15\_W_2$ scenario), the greatest possible upside NPV across scenarios (the highest flow, lowest demand $+15\_W_0$ scenario), and the greatest expected NPV for the middle runoff-development scenario ($+0\_W_1$). In all cases, faster (10-yr) timing and the sequencing of construction starting upstream yield results that dominate slower timing and initiation of construction from the downstream end of the system. In most cases, coordinated operation yields better results than hydropower-based operation because this provides greater ability to meet downstream withdrawal targets.

Using the results in Table 5, we identify the conservative strategy described in Section 2, which is the alternative that has the highest downside NPV in the scenario (e.g., high withdrawal, low runoff) that produces the lowest downside NPV for the largest number of alternatives. That alternative is the two-dam Beko Abo + Border configuration with small dams at both sites, and a coordinated operating rule. On the other hand, the risk-taking strategy (that has the highest upside NPV in the scenario that produces the highest upside NPV for the largest number of alternatives) is a three-dam combination of medium-sized dams, located at Beko Abo, Mendaya and Border. (Note that if the 1st and 99th percentile metrics are used rather than the 10th and 90th percentiles, the risk-taking strategy remains the same, but the conservative one is instead a single small dam at Beko Abo).

To assess the relative performance of different planning alternatives, we use the relative performance metrics ($OC_{j,i}$, $RR_{j,i}$, and $RU_{j,i}$), accounting for the flexibility provided by real options as described in Section 2. We compare the relative outcomes for the conservative strategy identified above with those for the risk-taking strategy, as well as for every other investment path that is not strictly dominated by these two strategies (i.e. all balanced strategies). There are 12 such balanced strategies, but eight of these are themselves inferior – for all three performance metrics – to at least one of the other balanced strategies, such that the problem collapses to a comparison of 6 non-dominated investment paths. In this way, the choice set containing the most attractive alternatives is reduced considerably (Figure 3).

Because we do not ourselves see *a priori* reasons for favoring or deriving a specific decision metric for comparing infrastructure performance across scenarios, the RDM-options framework as implemented here does not offer guidance on which of these 6 strategies is best (or 7, if the alternative measure of downside – the 1st percentile – is used). However, it does serve to highlight the tradeoffs between downside, expected and upside NPV. For example, a decision maker who selects the conservative strategy can look at the relative metrics to see that he might be losing US$7-35 billion of upside NPV across runoff and withdrawal scenarios, and US$2-17 billion of expected NPV, with the highest losses occurring if future water availability is high. On the other hand, the risk-taking strategy generates US$0-5 billion lower downside NPV across scenarios, and performs least well when water availability is low. In contrast, the three-dam alternative with medium Beko Abo, small Mendaya, and medium Border seems particularly well balanced (and which we use for the analysis of delay in Section 4.5). It only loses about US$0-3 billion of downside NPV and US$0-5 billion of upside NPV across scenarios.

4.4. The value of real options

The economic value of real options lies in the flexibility they provide to water resources planners and managers, given that the future state of the world is unknown. To better understand the potential value of this flexibility, we can examine more carefully how these options alter the performance of different planning alternatives in terms of lowest downside NPV – in the lowest water availability scenario – and highest upside NPV – in the highest water availability scenario (Figure 4). In Figure 4, black arrows indicate sequential investments along a particular investment path, i.e., the exercising of real options to build additional dams. The red arrows then show the reduction in downside NPV associated with downsizing real options, or the ability to operate large dams at lower levels. For simplicity, the value of changing operating rules is not shown, such that all outcomes are based on the operating rules that produce the best outcomes (results for alternative measures of downside and upside are available upon request from the authors).

The most attractive investments, shown in the upper right quadrant of Figure 4, always begin with a first project at Beko Abo. There are two such families of investment paths (or subsets of planning alternatives that remain possible following the specific investment decision of beginning with Beko Abo). The family with mostly higher downside NPV contains an initial small dam at Beko Abo, whereas the one with higher upside NPV begins with a medium dam at that site. Additional dams within these families then usually decrease downside NPV, but correspond to greater upside. As shown, the value of downsizing varies considerably across alternatives, and is lower for the family of investments starting with a small Beko Abo (which cannot be downsized). For some investment paths, downside NPV can be increased by almost US$2 billion with inclusion of downsizing options; this is particularly the case for the riskier investments located to the left of Figure 4 (e.g., several of the configurations including large dams at Border or Mendaya).

4.5. The Implications of the Grand Renaissance Dam

Because Ethiopia has already committed to building the Grand Renaissance Dam, we next examine the relative performance metrics for the alternatives that include this dam. The lost expected value for the best Grand Renaissance alternative (as defined relative to the full set of other alternatives by OC), ranges from US$3 billion–$7 billion across model scenarios (Figure 5). Upside decreases by $6 billion–$13 billion, and downside is lowered by $1–$4 billion. These changes in NPV are even higher if the Grand Renaissance Dam is constructed without including downsizing flexibility. For example, without downsizing flexibility, the reduction of expected NPV increases to $4 billion–$8 billion, the reduction of upside NPV increases to $9 billion–$15 billion, and the reduction in downside NPV increases to $2.5 billion–$7 billion across scenarios. Planning alternatives that include the Grand Renaissance Dam are less attractive because the project has high capital costs, has lower economic returns than Beko Abo as an initial investment, and renders infeasible the most economically attractive three-dam cascade alternative. Finally, compared to the balanced strategy identified at the end of Section 4.3 (medium Beko Abo, small Mendaya, and medium Border), the relative costs of the best Grand Renaissance Dam alternatives are $2–6 billion (OC), $5 –10 billion (RU), and $0.2–2 billion (RR). The only situations in which alternatives with the relative performance metrics of the Grand Renaissance Dam are favorable are if: (1) only two dams could be built (for financial or other reasons), and (2) flows increase and water withdrawals in Ethiopia remain low (results not shown).

4.6. The Costs of Delay

One option for dealing with uncertainty would be to delay investments and wait for more information. 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 adjust for the reduction in NPV due to waiting, and varying this discount rate from 2-6% in sensitivity analyses. To characterize an upper bound on value of delay, we assume for the purposes of illustration that perfect information on mean changes in future inflows and water withdrawals would be obtained in a specific number of years *x* (e.g., the deep uncertainty would be fully resolved in this time period). We then compare the change (i.e., the decrease in expected NPV from implementing the known "best" option under perfect information (after *x* years) with the change in expected NPV from immediately implementing, in the absence of information, the three previously identified investment strategies – balanced (medium Beko Abo, small Mendaya, and medium Border), conservative (small Beko Abo, small Border), and risk-taking (Beko Abo, Mendaya, and Border, all medium).

The analysis shows that the decrease in expected NPV from waiting to select the best alternative relative to the decrease in expected NPV from following a balanced strategy immediately is high. Waiting even five years is more costly than beginning construction immediately, no matter which inflows and withdrawals materialize, because of the forgone benefits from delaying investment (Figure 6, top panel). Results for upside NPV are similar, and downside is only higher for the waiting strategy if flows are reduced by 15% (low withdrawals) or 10-15% (high withdrawals and/or low discount rate). In addition, investments beyond the first project at Beko Abo could still be modified as additional information was obtained. Morevoer, initiating a first project quickly would allow learning that would be highly relevant for planning multiple dams on the same river (given the high correlations between the parameters that affect costs and benefits, e.g. flow conditions, local construction costs, the value of energy).

For the conservative strategy, waiting five years yields an improvement in expected NPV if inflows do not change or increase (Figure 6, middle panel), and/or if the discount rate is very low (2%). At a discount rate of 4%, delay performs less well under all conditions if the waiting period is increased to 8 years or more. In general, the cost of waiting decreases with increasing water withdrawals because the conservative strategy performs better under such conditions. Importantly, a modified conservative three-dam cascade (with an additional small dam added at Mendaya) dominates a strategy of delay. Finally, the expected NPV of the risk-taking strategy outperforms a 5-year delay strategy (with perfect information on flows and withdrawals) under all conditions (Figure 6, top panel), unless the discount rate is very low, withdrawals are high, and inflows decrease by 15%. Because no one expects uncertainty over future climate change to be resolved in anything like five to eight years, any of the three strategies for Blue Nile hydropower development described above would outperform a waiting strategy in terms of expected NPV.

5. Discussion

This paper described an analytical approach for better integrating uncertainty about climate change and other sources of uncertainty that affect river basins over a long time horizon into the problem of planning water resources infrastructure investments. The motivation for this approach arises from the challenges that such uncertainties present to the dominant planning models used in the academic water resources literature. The proposed method relies on simulation methods to generate performance metrics for different alternatives. The relative metrics for a reduced set of non-dominated alternatives selected using conservative, balanced and risk-seeking decision rules are then presented graphically across scenarios, in order to shed light on the robustness of specific alternatives to different conditions. We show that the best answer will vary with decision makers' risk preferences, as well as the weighting they ascribe to different scenarios that represent deep uncertainties. In this discussion, we focus on lessons from the application of this approach to the Blue Nile (acknowledging that they are particular to this site and decision problem), and also offer more general comments on strengths and limitations of the approach.

The specific results obtained from applying the method to the Blue Nile provide important insights into the economics of hydropower investments in Ethiopia. We find strong justification for the decision to move forward with the construction of an initial dam in the Blue Nile cascade. For the most attractive investment strategies – conservative, balanced, and risk-taking – and a realistic time horizon for collecting information about hydrological change and development uncertainties, the foregone benefits from delay exceed the potential benefits associated with obtaining that information. In addition, real options that would allow downsizing of dams and greater operational flexibility often prove valuable for managing risk, raising downside NPV by up to US$2 billion (as shown in Figure 4).

Given the caveats of our analysis discussed previously, the best alternatives do not include the Grand Renaissance Dam, but instead include a smaller dam at the Border site. This smaller Border project appears along with Beko Abo (in the conservative strategy) or Beko Abo and Mendaya (in the balanced or risk-taking strategies). Assuming the Grand Renaissance Dam will be completed as planned, our analyses suggest that a two-dam combination with Beko Abo as the second project is likely the best remaining alternative for a Blue Nile cascade. This initial investment in the Grand Renaissance Dam also creates an important economic tradeoff – between hydropower and irrigation – for Ethiopia, i.e. irrigation withdrawals upstream of the cascade will reduce hydropower generation. From this perspective, Egypt might be pleased that Ethiopia has committed itself to major hydropower infrastructure on the Blue Nile, even though the large storage volume of the reservoir created by the Grand Renaissance Dam does create opportunities for strategic behavior and adverse short-term filling effects.

The poor relative performance of planning alternatives containing the Grand Renaissance Dam stem from that project's high capital costs, its lower net benefits relative to Beko Abo, and the fact that it reduces the viability of the more robust three-dam cascade alternatives that contain a dam at Mendaya. Even if the Grand Renaissance Dam were operated at low levels to make room for Mendaya, these first two disadvantages make alternatives containing it considerably less attractive than those that start with a dam at Beko Abo. The advantages of three-dam alternatives with moderately-sized infrastructures over two-dam configurations with larger dams are largely due to the higher cost-effectiveness and greater flexibility allowed by the smaller projects, i.e. the combination of high hydropower output relative to capital requirements.

Our RDM-real options application necessarily focused on a specific river basin, but similar problems of dealing with uncertainty permeate water resources planning, and we believe that there are several insights from this work that are of general interest. First, a challenging step in this approach is the partitioning of uncertainties into the deep and probabilistic risk categories. In our specific application, modest changes in future water demands and runoff (both of which are exceedingly hard to predict over a long time horizon) were shown to have significant effects on the net benefits of investment alternatives (Table 5). Lower runoff and greater upstream water withdrawals both decrease hydropower production and increase reservoir filling times. Higher temperatures due to climate change increase other pressures in the Nile Basin system, e.g., increased crop water demands and reservoir evaporation rates. These factors, which diminish the economic returns from dams, will likely be important in other water scarce river basins. They also have important implications for the sequencing of investments. For example, individual projects that may look attractive on their own (e.g., larger dams in the Blue Nile gorge) may not perform as well as multi-project alternatives. Other factors may be hard to project into the future, and work that explores the importance of a wider array of uncertainties under climate change (e.g., Jeuland [2010]) and focuses on scenario development for climate change analysis (e.g., Laurent and Cai [2007]), remains important.

Second, it will not usually be possible to identify a single planning alternative (as characterized by a specific package of features such as project configuration sizing, operating rules, etc.) that is dominant across plausible future conditions, particularly if decision makers are concerned about downside and upside outcomes. If decision-maker preferences are uncertain, this will add additional complexity to the challenge of choosing investments. Yet the likelihood of non-dominance in many decision problems must be acknowledged and accommodated, and the analytical approach presented here generates insight into the relative upside and downside associated with different investment strategies, which can be utilized to inform and support decision-making.

Third, using analytical methods that explicitly account for flexible options is critical to developing a better understanding of the tradeoff between downside risks and upside potential. If higher-upside investments (e.g., larger dams) can be modified – for example, if operating capacity can be varied to handle fluctuations in inflow and downstream demands – additional capital costs may be justified by higher downside returns if poor conditions materialize. Similarly, the advantages of modular designs with multiple components that allow for recourse are well known [*Sanchez and Mahoney*, 2002]. The value of incorporating flexibility into project design will of course depend on the relative balance of the cost of that flexibility and the extent to which it moderates poor outcomes. In this sense, future study is needed to determine whether the Grand Renaissance Dam may accommodate an improved multi-dam investment strategy in the Blue Nile. And of course, the flipside of infrastructure flexibility is enhanced demand and operational management: poor outcomes can be avoided through more effective and nimble management of water withdrawals and changed release patterns from reservoirs.

Although we think the analytical framework developed in this paper will be valuable in many situations, a number of limitations (and potential extensions) of our application should be highlighted. First, as discussed above, perhaps the most important challenge associated with this approach is that of determining which uncertainties in the planning problem should be considered deep uncertainties, and which uncertainties can be subjected to probabilistic risk analysis. Such choices necessarily involve judgment (by analysts or decision makers), and imply tradeoffs between analytical tractability and the reliability of conclusions obtained from the analysis. They should also be informed by analytical work that identifies key sensitivities in the decision problem.

Second, our incorporation of changes in runoff, which focused on uniform step changes, were illustrative and not reflective of the state-of-the-art in modeling climate change effects on hydrological systems. A more complete planning exercise would incorporate more realistic changes that include spatially and temporally differentiated downscaling of projections (e.g., incorporating the non-stationary evolution of flows). Such an approach might alter our conclusions about the relative advantage of balanced investment strategies in this basin (compared with conservative and risk-taking strategies). In particular, since changes would occur gradually over time, it seems likely that the decreased relative downside NPV of the risk-taking strategy is pessimistic, and conversely the increased relative downside NPV of the conservative strategy is optimistic. In other words, if runoff decreases, the risk-taking strategy performs more poorly, and our approach of assuming step changes in runoff makes it look worse that it will really be because runoff actually only changes slowly. Incorporating gradual changes would also reinforce our conclusions about the undesirability of delaying balanced investment strategies, since the cost of delay is lowest under sharply declining inflows, which is unlikely to happen in the near term. Finally, because the assumed discount rate has such a large influence on our economic outcome indicators, we do not think that relaxing the assumption concerning stationarity would lead to substantially different conclusions. However, the interaction of time-dependent changes in flows with discounting would tend to reduce the sensitivity of economic outcomes to projected changes in runoff (which occur only gradually) and this issue should be investigated further.

Third, the results obtained from our models depend on a number of important assumptions about model parameters and definitions of outcome metrics. For example, we use the best information currently available to monetize basin-wide impacts of Blue Nile dams, but such data remain limited. In fact, one of the most important drivers of uncertainty in the NPV outcomes relates to the value of (demand for) the hydropower they would produce [*Jeuland*, 2010]. Also, the costs (to recessional agriculture and ecosystems) and benefits (flood control) of regulating flows in the Blue Nile downstream of Ethiopia remain unclear at this time, and the distribution of costs and benefits across countries and economic sectors require further study. Finally, though none of our main results were found to be sensitive to the percentiles (of the NPV distribution) chosen for definition of downside and upside metrics, they did alter the composition of the infrastructure projects included in the conservative strategy and more generally would affect the magnitude of the relative metrics used for comparing investment paths. Sensitivity analyses around the definitions of such metrics should therefore be standard practice when this approach is used.

Fourth, work on the costs and potential of real options should be extended to consider a more complete set of infrastructure and management alternatives and coordination rules. Including more features (such as reservoir filling rates, changes in turbine capacity, different sequencing of projects or dam construction along tributaries) and combining simulation and optimization methods to enhance operating rules could reveal new, possibly more attractive investment possibilities. Similarly, work on better understanding timing decisions with regards to real options could be another fruitful area for additional research. Finally, the distributional incentives of planning alternatives comprised of different features would need to be explored in order to better understand the feasibility of cooperative financing and management for them.

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Lexicon

Balanced strategy: Any investment alternative that is not strictly dominated (e.g., inferior) by the conservative and risk-taking strategies, considering the outcomes across all potential scenarios and the three relative performance metrics (downside, expected and upside NPV).

Conservative strategy: The investment alternative that selects the alternative with the highest downside NPV in the scenario that produces the lowest downside NPV for the largest number of alternatives.

Downside NPV: The 10th percentile of the NPV distribution for a planning alternative in a particular scenario.

Expected NPV: The mean value of the NPV distribution for a planning alternative in a particular scenario.

Analysis: A Monte Carlo analysis of economic outcomes for a single alternative in a specific water withdrawal and climate scenario using the hydro-economic simulation model.

Planning alternative (also referred to as alternative): A specific combination of design features and operating rules.

Robust-decision making (RDM): A class of methods that are used to identify robust strategies, or strategies that perform relatively well, compared to the alternatives, across a wide range of plausible future scenarios.

Real options: Features of infrastructure or managerial systems that allow for physical changes in configuration or operations to effectively respond to conditions that vary over time (e.g., options to defer, expand, contract, abandon, switch use, or otherwise alter a capital investment).

Recourse: The ability to take corrective action after an event has taken place.

Risk-taking strategy: The investment alternative that generates the highest upside NPV in the scenario that produces the highest upside NPV for the largest number of alternatives.

Scenario: In this paper, a unique combination of hydrological and water demand conditions.

Upside NPV: The 90th percentile of the NPV distribution for a planning alternative in a particular scenario.

Figure legends

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 relationships between risk (downside NPV) and rewards (upside NPV) 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 3. The relative performance metrics of the various preferred investment strategies: conservative (highest worst case downside NPV), risk-taking (highest best-case upside NPV), and balanced strategies that are not strictly dominated by these, across inflow scenarios, with W0 (left) and W2 (right) withdrawals

Figure 4. The maximum upside (high flow and low water withdrawals) and minimum downside (low flow and high water withdrawals) of the different infrastructure development paths. Black arrows depict movements that correspond to sequential dam projects (exercising real options); red dotted arrows show the change in downside NPV that comes from incorporating “downsizing” options into dam designs.

Figure 5. 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 6. The cost of waiting relative to balanced (top), conservative (middle), and risk-taking (bottom) strategies

Table 1. Summary of runoff and water demand scenarios

Scenarios	**# of scenarios**	**Description**
Water withdrawal conditions (Status quo, moderate and high development)	3	W_0: Existing water withdrawals and regulating infrastructures W_1: W_0 withdrawals + half of potential expansion in Master Plans for Sudan and Ethiopia up to 1959 treaty allocations (for Sudan) W_2: W_0 withdrawals + 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 (7 x 3)	

Notes: Demand scenarios correspond to three levels of water withdrawals in the Blue Nile as informed by Country Master Plans; Uniform and stationary % changes are applied to historical runoff for the hydrological conditions

Table 2. 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 3. Summary of project features

Feature	**Single Dams**	**2-Dam Cascade**	**3-Dam Cascade**	**4-Dam Cascade**
Configuration [a]	Karadobi Beko Abo Mabil Mendaya Border	Karadobi + Mabil Karadobi + Mendaya Karadobi + Border Beko + Mendaya Beko + Border Mabil + Border Mendaya + Border	Karadobi + Mabil + Border Karadobi + Mendaya + Border Beko + Mendaya + Border Mabil + Mendaya + Border	Karadobi + Mabil + Mendaya + Border
Sequencing	Upstream to downstream Downstream to upstream	Upstream to downstream Downstream to upstream	Upstream to downstream Downstream to upstream	Upstream to downstream Downstream to upstream
Timing [b]	No timing feature	10 years apart 20 years apart	10 years apart 20 years apart	10 years apart 20 years apart
Sizing [c]	Small Medium Large	All small All medium Small 1, medium 2 Small 1, large 2 Medium 1, small 2 Medium 1, large 2 Large 1, small 2 Large 1, medium 2	All small All medium Small 1, others medium Large 2, others small Small 2, others medium Large 2, others medium Small 3, others medium Large 3, others medium Large 3, others small	All small Small 3, others med
Operating Rule [d]	Standard (Max HP) Strong coordination	Standard (Max HP) Strong coordination	Standard (Max HP) Strong coordination	Standard (Max HP) Strong coordination

[a] Not all configurations 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 was found to yield inferior NPV in all cases and was thus explored only for the middle-size dam combinations and hydropower operating rule.

[c] Large sizing for Mendaya and Border; small/medium only for the other three sites due to limitations of previous studies.

[d] With strong coordination, the Blue Nile minimum releases from reservoirs are increased when storage in the downstream High Aswan Dam drops below 60 bcm. These releases are specified as: Karadobi = 1; Beko Abo = 1.2; Mabil = 1.2; Mendaya = 2; Border = 2.4 (all in bcm/month).

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)

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							Beko (M) (18.3, 0.04)	Beko (S) + Bord (S) (24.7, 0.12)	Beko (S) + Mend (S) + Bord (S) (26.4, 0.36)	Beko (M) (17.1, 0.66)	Beko (S) + Bord (S) (22.9, 1.2)	Beko (S) + Mend (S) + Bord (S) (24.5, 1.3)	Beko (S) (15.4, 1.8)	Beko (S) + Bord (S) (21.1, 2.6)	Beko (S) + Mend (S) + Bord (S) (22.6, 2.4)
B	1/2	1/2						Beko (M) (20.0, 0.03)	Beko (M) + Bord (S) (27.3, 0.23)	Beko (S) + Mend (S) + Bord (S) (28.9, 0.19)	Beko (M) (19.2, 0.33)	Beko (M) + Bord (S) (25.5, 0.94)	Beko (S) + Mend (S) + Bord (S) (27.1, 0.74)	Beko (M) (17.3, 1.1)	Beko (M) + Bord (S) (23.2, 2.2)	Beko (S) + Mend (S) + Bord (S) (24.8, 1.6)
C	1/3	1/3	1/3					Beko (M) (21.8, 0.03)	Beko (M) + Bord (S) (29.8, 0.15)	Beko (M) + Mend (S) + Bord (M) (31.5, 1.4)	Beko (M) (21.0, 0.33)	Beko (M) + Bord (S) (28.0, 0.63)	Beko (S) + Mend (S) + Bord (S) (29.5, 0.49)	Beko (M) (19.2, 0.75)	Beko (M) + Bord (S) (25.5, 1.5)	Beko (S) + Mend (S) + Bord (S) (27.0, 1.1)
D	1/4	1/4	1/4	1/4				Beko (M) (23.2, 0.02)	Beko (M) + Bord (M) (32.1, 0.37)	Beko (M) + Mend (M) + Bord (M) (34.9, 1.1)	Beko (M) (22.4, 0.17)	Beko (M) + Bord (S) (29.9, 0.47)	Beko (M) + Mend (S) + Bord (M) (31.4, 2.7)	Beko (M) (20.6, 0.57)	Beko (M) + Bord (S) (27.3, 1.2)	Beko (S) + Mend (S) + Bord (S) (28.9, 0.8)
E	1/5	1/5	1/5	1/5	1/5			Beko (M) (25.3, 0.02)	Beko (M) + Bord (M) (35.4, 0.30)	Beko (M) + Mend (M) + Bord (M) (38.6, 0.9)	Beko (M) (24.9, 0.13)	Beko (M) + Bord (M) (33.3, 1.1)	Beko (M) + Mend (M) + Bord (M) (35.8, 2.1)	Beko (M) (23.0, 0.45)	Beko (M) + Bord (S) (30.6, 0.92)	Beko (M) + Mend (S) + Bord (M) (32.5, 3.7)
F	1/7	1/7	1/7	1/7	1/7	1/7	1/7	Beko (M) (28.7, 0.01)	Beko (M) + Bord (L) (41.0, 0.94)	Beko (M) + Mend (M) + Bord (M) (44.4, 0.6)	Beko (M) (28.6, 0.09)	Beko (M) + Bord (M) (39.3, 0.77)	Beko (M) + Mend (M) + Bord (M) (42.4, 1.5)	Beko (M) (27.0, 0.32)	Beko (M) + Bord (M) (36.3, 1.5)	Beko (M) + Mend (M) + Bord (M) (39.2, 2.6)
G			1/5	1/5	1/5	1/5	1/5	Beko (M) (32.1, 0.0)	Beko (M) + Bord (L) (47.3, 0.01)	Beko (M) + Mend (M) + Bord (M) (50.8, 0.0)	Beko (M) (32.3, 0.0)	Beko (M) + Bord (L) (45.8, 0.16)	Beko (M) + Mend (M) + Bord (M) (49.1, 0.09)	Beko (M) (30.9, 0.01)	Beko (M) + Bord (M) (41.9, 0.19)	Beko (M) + Mend (M) + Bord (M) (45.6, 0.52)
H				1/4	1/4	1/4	1/4	Beko (M) (33.8, 0.0)	Beko (M) + Bord (L) (50.5, 0.0)	Beko (M) + Mend (M) + Bord (M) (53.8, 0.0)	Beko (M) (34.2, 0.0)	Beko (M) + Bord (L) (49.3, 0.03)	Beko (M) + Mend (M) + Bord (M) (52.4, 0.02)	Beko (M) (32.8, 0.0)	Beko (M) + Bord (L) (45.3, 0.29)	Beko (M) + Mend (M) + Bord (M) (49.0, 0.18)
I							1	Beko (M) (40.5, 0.0)	Beko (M) + Bord (L) (60.8, 0.0)	Beko (M) + Mend (M) + Bord (M) (63.9, 0.0)	Beko (M) (41.0, 0.0)	Beko (M) + Bord (L) (61.2, 0.0)	Beko (M) + Mend (M) + Bord (M) (63.6, 0.0)	Beko (M) (40.6, 0.0)	Beko (M) + Bord (L) (59.4, 0.0)	Beko (M) + Mend (M) + Bord (M) (62.5, 0.0)

Notes: Cases are constructed by assigning specific probabilities to flow scenarios for the purposes of illustration. Dark lines indicate where the best choice (in terms of highest expected NPV) of infrastructure features changes. Sizes indicated by: (S) Small; (M) Medium; (L) Large.

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

Combination	**Worst case scenario downside NPV (-15_W_2)**	**Mid case scenario expected NPV ($+0\_W_1$)**	**Best case scenario upside NPV ($+15\_W_0$)**
1-Dam	Beko Abo (S), coordinated operation 5.6 billion	Beko Abo (M), coord. operation 26.7 billion	Beko Abo (M), coord. operation 67.8 billion
2-Dams	Beko (S) + Border (S), coord. operation 5.8 billion	Beko (M) + Border (M), hydro-based operation 36.1 billion	Beko (M) + Border (L), hydro-based operation 105.3 billion
3-Dams	Beko (S) + Mend (S) + Border (S), coord.operation 5.1 billion	Beko (M) + Mend (M) + Border (M), coord. operation 39.4 billion	Beko (M) + Mend (M) + Border (M), coord. operation 114.4 billion
4-Dams	Kar (S) + Mab (S) + Mend (S) + Border (S), coord. operation -0.8 billion	Kar (S) + Mab (S) + Mend (S) + Border (S), coord. operation 22.7 billion	Kar (S) + Mab (S) + Mend (M) + Border (S), coord. operation 72.9 billion

Notes: Shading indicated “best” configuration in terms of a specific criterion (by column); 10-year timing always dominates, as does upstream to downstream sequencing. Sizes indicated by: (S) Small; (M) Medium; (L) Large. In this particular application, the “best” performing combination of infrastructures is not sensitive to the definition of the metric used to measure upside potential (90th or 99th percentile); however, the small Beko Abo dam becomes “best” (instead of the two-dam combination that also includes Border) the grounds of downside NPV when the 1st percentile is used for downside risk.