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The cost of noncooperation in international river basins

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[1] In recent years there has been a renewed interest for water supply enhancement strategies in order to deal with the exploding demand for water in some regions, particularly in Asia and Africa. Within such strategies, reservoirs, especially multipurpose ones, are expected to play a key role in enhancing water security. This renewed impetus for the traditional supply-side approach to water management may indeed contribute to socioeconomic development and poverty reduction if the planning process considers the lessons learned from the past, which led to the recommendations by the World Commission on Dams and other relevant policy initiatives. More specifically, the issues dealing with benefit sharing within an efficient and equitable utilization of water resources are key elements toward the successful development of those river basins. Hence, there is a need for improved coordination and cooperation among water users, sectors, and riparian countries. However, few studies have explicitly tried to quantify, in monetary terms, the economic costs of noncooperation, which we believe to be important information for water managers and policy makers, especially at a time when major developments are planned. In this paper we propose a methodology to assess the economic costs of noncooperation when managing large-scale water resources systems involving multiple reservoirs, and where the dominant uses are hydropower generation and irrigated agriculture. An analysis of the Zambezi River basin, one of the largest river basins in Africa that is likely to see major developments in the coming decades, is carried out. This valuation exercise reveals that the yearly average cost of noncooperation would reach 350 million US$/a, which is 10% of the annual benefits derived from the system.

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1. Introduction

[2] For water managers, the 1980s were marked by a major paradigm shift: the traditional supply-enhancement strategy that had been implemented to meet the growing water demands throughout much of the 20th century was being replaced by a more loosely structured paradigm, called integrated water resources management (IWRM), which emphasized, among other things, the need to consider both supply and demand when planning and managing water resources [*Davis*, 2007]. Although the definition of supply does not pose any problem, the term *demand* can have different meanings to different people: for many engineers, demand and requirement are simply equivalent, whereas economists do make a distinction as they consider that requirement, unlike true demand, does not embed scarcity-sensitive parameters [*Griffin*, 2006]. When water resource planning was dominated by the supply-enhancement strategy, the use of requirement was simply fueling the planning process as increasing "demands" could only be met with larger supplies and so on. In many industrialized countries, this strategy has now reached a limit because water supplies are physically limited and the construction costs of large-scale hydraulic infrastructure are escalating. As a spillover effect, the construction of these infrastructure also came to a virtual standstill in developing countries even though the potential had not yet been exhausted.

[3] For the dam industry, this paradigm shift led to the establishment of the World Commission on Dams, which was initiated by IUCN and the World Bank. The report, released in 2000 [*WCD*, 2000], made several recommendations to improve the economic, social, and environmental performances of large-scale hydraulic infrastructure. The dam industry, donors, and governments were forced to adopt precautionary principles which slowed the development of new water resources. The new discourse was that the focus should be on how we use water and on water efficiency and productivity, and no longer on large-scale infrastructure [*Bouwer*, 2002]. At the same time, public expenditures in irrigated agriculture had already declined, not only in developed countries but also in Asia and Africa [*Rosegrant*, 1997]. Twenty years later, as a result of this policy, the contribution of irrigation to food production has decreased, and many countries are left but with no choice to rely on rainfed agriculture and/or on trading to meet the growing demand for food due to sustained population growth.

[4] After two decades of rather slow water resources development, there are now signs that the construction of storage facilities and irrigation schemes is on the rise again.

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For example, the New Partnership for Africa's Development (NEPAD) has launched the African Water Facility whose mission is to attract investments that are required in the water sector. The comparison with industrialized countries, where the per capita storage capacity can be as high as 3500 m^3 compared to 50 m^3 in Africa, also fueled the revival of the hydraulic mission in the South. In terms of hydroelectricity, the difference between the North and the South is even more staggering: in France, for instance, 100% of the hydroelectric potential is used compared to only 4% in Africa [*WEC*, 2001].

[5] This renewed impetus is also perceived as an important tool to develop adaptive management strategies to deal with climate change [*Haas et al.*, 2009]. In the agricultural sector alone, the warming of the atmosphere due to greenhouse gases will likely affect crop yields through increased crop water requirements, changing rainfall patterns and more frequent extreme temperature events. Together with well-functioning institutions and demand management measures, storage facilities can indeed reduce the vulnerability of water users by providing managerial flexibility [*Stakhiv*, 1998; *UNESCO*, 2009; *UN-Water*, 2010]. Such flexibility is particularly valuable, not only in irrigated agriculture, but also for hydropower generation, and municipal and industrial water supply.

[6] In international river basins, a wise management of water resources is even more challenging due to the additional, fragmented, political layer. Without a single set of water law and policy, the various political jurisdictions involved or impacted by an infrastructural water project are more likely to end up on a collision course leading to disputes and potential conflicts. Hence, with little or no coordination among riparian countries, the specter of unilateral developments is still a major threat to the peaceful and efficient sharing of international waters. As a matter of fact, in the absence of an international agreement, countries have an incentive to pursue a fait accompli policy and to develop their water resources as soon as possible in order to be in a stronger position at the negotiation table. This short-term strategy is likely to become counterproductive in the long run as unilateral water projects can hamper the economic development of the basin as a whole, affecting the regional economic growth and stability of the region [*Wu and Whittington*, 2006].

[7] Another threat to the peaceful sharing of international waters is related to the 2007–2008 global food crisis. Throughout much of the developing world, private investors and governments alike started investing massively in agricultural lands as part of a strategy to reduce their exposure to highly volatile food prices and to achieve food security [*Cotula et al.*, 2009]. According to *Schutter* [2009], since 2006, between 15 and 20 millions of hectares of farmland in developing countries are leased or have been bought by foreign investors. For recipient governments, who usually own the lands, this is perceived as an opportunity to turn underutilized or marginal lands into a source of revenues while providing employment to the rural poors. Since most of those lands are close to water resources so that they can be irrigated, there is a threat that the so-called "land grabbing" will interfere with the expansion of irrigated agriculture that will occur to meet increasing domestic food demands.

[8] To deal with water allocation issues in international river basins, some authors have suggested to shift the focus from sharing the water itself to sharing the benefits derived from the use and nonuse of water [*Molle et al.*, 2007]. The main argument is that by sharing the benefits one turns the zero-sum game water allocation problem into a positive-sum game whereby "win-win" solutions can emerge [*Sadoff and Gray*, 2002; *Sadoff and Muller*, 2009]. In the paper by *Sadoff and Gray* [2002], the term "benefits" includes several aspects: benefits from the river, to the river, beyond the river, and reduced costs because of the river. The concept therefore rests on the assumption that cooperation is beneficial to the basin as a whole, and that the benefits can be fairly redistributed [*Dombrowsky*, 2009].

[9] This paper addresses the first assumption and proposes a methodology to assess the opportunity cost, i.e., the benefits forgone, associated with unilateral development projects. The second assumption (the redistribution of benefits and the issue of equity) has been addressed through the development of measurable criteria based on socioeconomic and hydrologic indicators [*Van der Zaag and Savenije*, 2002], or through game theory [*Wang et al.*, 2003; *Madani*, 2010].

[10] Even though all water-related sectors are important, the proposed methodology is developed for river basins where the dominant uses are hydropower generation and irrigated agriculture. This is because (1) these two users are likely to be at the margin, and (2) their potential impact on local and regional economies is significant. The proposed methodology focuses on the benefits derived from the river and relies on hydroeconomic modeling to represent spatially distributed supplies and economic demands in a river basin. The case study of the Zambezi River basin is used to illustrate the methodology. This river basin is likely to see major developments in the coming decades as its hydropower and irrigation potentials are still largely untapped, and populations are expected to double by 2050.

[11] The paper is organized as follows: Section 2 describes the methodology and the case study. Results are presented in section 3, followed by conclusions in section 4.

2. Materials and Methods

2.1. Key Assumptions and Geopolitical Context

[12] The proposed approach to assess the cost of noncooperation rests on two key assumptions: (1) riparian countries have access to various donors to develop their water resources, and (2) there is no international consensus on environmental and social standards attached to public infrastructure investment projects. The rationale for these two assumptions must be found in the strengthening of South-South cooperation, which is exemplified by the increasingly important role played by emerging countries like China and Brazil. In Africa, China has become a major alternative lender, providing competitive financial packages often linked to infrastructure projects like dams [*Naidu and Mabazima*, 2008]. However, as pointed out by *McDonald et al.* [2009], Chinese import-export banks have not yet adopted environmental and social policies in line with international standards, arguing that developing countries should not be held to the same standards as industrialized nations. China's policy of not interfering with other nation's internal

affairs is also instrumental in strengthening ties with African nations, therefore giving African governments leverage in their relations with industrialized countries.

[13] The fact that developing countries seeking to develop their own water resources are no longer tied up with Western donors has important implications for the assessment of the cost of noncooperation. For *Whittington et al.* [2005], for example, the economic value of cooperation in the Nile basin is derived by comparing various development scenarios with a *status quo* scenario representing the situation around 2005. They made the assumptions that (1) without cooperation, the riparian countries would not be able to raise the funds required to develop their projects, and (2) all large-scale infrastructure projects, regardless of their purpose (e.g., irrigation, hydroelectricity), do require approval from the other riparian countries. These two assumptions are relaxed in this paper because, in recent years, there have been signs that the road toward the establishment of a cooperative framework will be a long one. In the Nile, for example, the Entebbe agreement, which calls for the riparian countries to reallocate the Nile waters was signed in 2010 by Ethiopia, Tanzania, Rwanda, Uganda, and Kenya. Egypt and Sudan, who receive the lions share of the Nile water according to the 1959 treaty between these two countries, oppose the Entebbe agreement. In the Zambezi, Zambia refuses to sign and ratify the Zambezi Watercourse Commission (ZAMCOM) Protocol on the grounds that the protocol does not adequately capture her contribution (more than 40%) to the Zambezi river.

[14] From the above discussion, it seems that the current situation in a river basin can no longer be considered as a baseline against which various development trajectories could be compared to assess the gain of cooperation. Rather, the baseline must be a scenario in which the riparian countries develop their own water resources in a noncooperative way, independently of each other. The second scenario, on the other hand, must represent a cooperative development path leading to a benefit sharing arrangement. As indicated earlier, this paper focuses on the economic benefits derived from the river [*Sadoff and Gray*, 2002], which is often perceived as an important tool for socioeconomic development in the South where much of the new large-scale hydraulic infrastructure will be built in the coming decades. The comparison between the economic benefits derived from the two scenarios, i.e., the benefits that can be achieved with or without cooperation, will reveal the cost of noncooperation (the opportunity cost associated with unilateral developments in the riparian countries).

[15] The proposed methodology to assess to cost of noncooperation in international river basins also requires that the distinction be made between rival and nonrival uses. Nonrivalness is observed when users are not in competition for the same unit of water. In that case, the value of the last unit of water is the sum of the marginal values of the nonrival users since the demand curves can be summed up vertically as illustrated in Figure 1. Hence, it is the presence of rival users that requires coordination to prevent tensions over shared waters. In river basins where the dominant uses are irrigated agriculture and hydropower generation, irrigators are rival users; the consumptive nature of irrigation activities, even in the presence of return flows, implies that water in irrigated agriculture is a rival good. In contrast, provided that there is enough storage capacity, power companies are essentially nonrival users as a unit of water released by one dam can be used by the downstream one, while the capacity to store water in a reservoir provides a power company with some form of independence with respect to its upstream competitors. Of course this independence cannot last forever (the size of a reservoir is limited) but the bigger the reservoir is, the longer it will be. Consequently, the marginal water value at one site is thus the sum of the values of downstream power stations. Note that this assumption is no longer valid if the system is in a transient state like, for example, the filling of a newly

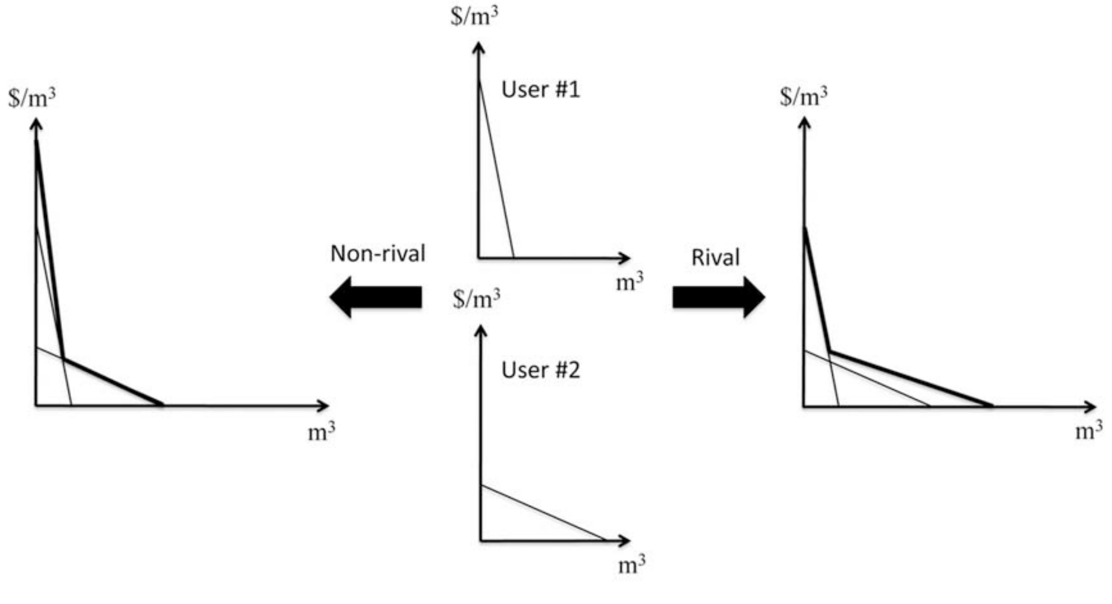

Figure 1. Rival versus nonrival users: aggregation of demand curves.

constructed reservoir, or for poorly designed storage power plants with substantial evaporation losses. In the case of a cascade of run-of-the-river power plants, this assumption is also not valid for short-term (hourly–daily) operation, when power companies may have conflicting release schedules. However, when dealing with mid to long-term operation (beyond the week), run-of-the-river power stations can be considered as nonrival users since a power station, through its own operation, cannot prevent the others from producing.

[16] As a result of this distinction between rival and nonrival uses, the decision to divert one more unit of water to an irrigation scheme will depend on whether the at-source value of irrigation water is larger than the at-source water value for all downstream marginal users. At-source water value is observed at a location where bulk water is diverted, whereas the at-site corresponds to the value of water delivered to the users, e.g., the farmer at the end of the conveyance and distribution system. At-site water values are usually larger than at-source ones since they include losses in the system as well as conveyance costs. To study intersectoral allocation choices, at-source water values must be used [*Young*, 2005]. Those marginal water values, the benefits and the allocation decisions, can all be derived from hydroeconomic models, which can represent individual, spatially distributed, water projects including demand sites, reservoirs, and diversions. Because water supplies are inherently uncertain, allocation policies (and thus water values) are best derived by stochastic hydroeconomic models with a probabilistic description of the hydrologic uncertainty [*Philbrick and Kitanidis*, 1999; *Tilmant et al.*, 2008]. Moreover, adopting a stochastic formulation also allows us to derive the statistical distribution of the cost of noncooperation, therefore increasing the scope of the analysis by bringing in the notion of risk, which was often overlooked in previous studies [*Whittington et al.*, 2005; *Fisher et al.*, 2005]. In this study, a stochastic dual dynamic programming (SDDP) algorithm is implemented to solve the high-dimensional (stochastic hydroeconomic) optimization problem resulting from the individual representation of the key elements of the system. As explained later, SDDP will be used to solve the allocation problem corresponding to each scenario.

2.2. Hydroeconomic Modeling

[17] As its name indicates, hydroeconomic modeling combines economic management concepts with an engineering level of understanding of a hydrologic system [*Heinz et al.*, 2007]. Hydroeconomic models integrate spatially distributed water resources, economic values, infrastructure, and management policies. Economic water demands, which are value (scarcity) sensitive, are integrated into a network built around arcs and nodes: the former usually represent natural inflows to the system, canals, the river network, whereas the nodes represent confluences, reservoirs, abstraction points, demand sites, etc. Hydroeconomic models have been developed and tested in various river basins around the globe. *Rosegrant et al.* [2000] and *Cai et al.* [2003], for example, analyze irrigation-dominated river basins in South America and central Asia with a hydroeconomic model. *Ringler et al.* [2004] adopts a similar formulation to study the optimal flow allocation in the Mekong River Basin. In a series of papers, *Ward and Michelsen* [2002] and *Ward et al.* [2006] investigate the hydrologic and economic impacts of various policy options in the Rio Grande Basin using a hydroeconomic model. *Fisher et al.* [2005] assess the value of cooperation in the Middle East (Israel, Palestine, Jordan) by optimizing the use of water with a deterministic hydroeconomic model. Hydroeconomic modeling is also a key component to integrate climate change into water resources planning [*Jeuland*, 2009]. Recent reviews on hydroeconomic modeling can be found by *Harou et al.* [2009] and *Brouwer and Hofkes* [2008].

[18] The typical structure of an optimization-based hydroeconomic model consists of an objective function to be maximized (or minimized) subject to physical, institutional and/or economical constraints. Since water allocation problems often involve multiple periods (day, week, month, year), the objective function is usually the sum of the one-stage benefit (cost) functions over the planning period. For many water resources allocation problems, the one-stage benefits may depend on both the allocation decisions and the status of the system (e.g., how much water is available).

[19] Denoting t as the index of time (stage), T as the end of the planning period, b_t as the one-stage benefit function at stage t, $\mathbf{x}$ as the vector of allocation (decision) variables, $\mathbf{w}$ as the vector of state variables, $\mathbf{q}$ as the vector of stochastic inflows, α as the discount factor, f as the transition from state t to stage $t + 1$, g as the set of functions constraining the decisions, h as the set of functions constraining the state, then the optimization problem can be written as

$$Z^* = \max_{\mathbf{x}_t} \left\{ \mathop{\mathbb{E}}_{\mathbf{q}_t} \left[\sum_{t}^{T} \alpha_t b_t(\mathbf{w}_t, \mathbf{x}_t) + \alpha_{T+1} \nu(\mathbf{w}_{T+1}) \right] \right\} \tag{1}$$

subject to

$$g_{t+1}(\mathbf{x}_{t+1}) \leq 0, \tag{2}$$

$$h_{t+1}(\mathbf{w}_{t+1}) \leq 0, \tag{3}$$

$$\mathbf{w}_{t+1} = f_t(\mathbf{w}_t, \mathbf{x}_t, \mathbf{q}_t), \tag{4}$$

where $\mathbb{E}$ is the expectation operator and Z^* is the total benefit associated with the optimal solutions $(\mathbf{x}_1^*, \mathbf{x}_2^*, \ldots, \mathbf{x}_T^*)$.

2.3. Stochastic Dual Dynamic Programming

[20] Stochastic dynamic programming (SDP) can be used to recursively solve the optimization problem (1)–(4). The SDP functional equation is

$$F_t(\mathbf{s}_t, \mathbf{q}_{t-1}) = \max_{\mathbf{x}_t} \; \{ \mathop{\mathbb{E}}_{\mathbf{q}_t | \mathbf{q}_{t-1}} [b_t(\mathbf{s}_t, \mathbf{q}_t, \mathbf{x}_t) + \alpha_{t+1} F_{t+1}(\mathbf{s}_{t+1}, \mathbf{q}_t)]\}, \tag{5}$$

where F_{t+1} is the benefit-to-go function. The solution of (5) requires the discretization of the state space, which leads to an exponential growth of the number of combinations of discrete states that quickly become overwhelming even for modern computers (this is the so-called curse of dimensionality). Here, the high dimensionality comes from the fact that (1) we need a fairly detailed representation of the river basin so as to make a distinction between existing and new irrigation and/or hydropower projects, and (2) we want to capture the hydrologic uncertainty and its impact on allocation decisions, marginal water values, and on benefits. This second point is important to derive a statistical distribution of the cost of noncooperation, and assess the hydrological risk faced by riparian countries. To deal with the dimensionality issue, we solve the multistage decision making problem with stochastic dual dynamic programming (SDDP), an extension of SDP that can handle a much larger state space. SDDP abates the curse of dimensionality by solving the SDP within a carefully chosen subset of the state space $(\mathbf{s}_t, \mathbf{q}_{t-1})$ and by constructing a locally accurate approximation of the benefit-to-go function F_t through simulation, sampling, and function approximation. The SDDP algorithm has been described in detail by *Goor et al.* [2011] and in *Tilmant et al.* [2007]; section 2.3 only presents the solution strategy and the main equations.

[21] SDDP is a combination of SDP and nested Benders decomposition with the former being able to handle a large number of stages but not a large state space, whereas the latter can handle a large state space but not a large number of stages. The Bellman functions are no longer stored in tables but in the form of nested Benders cuts. At each stage t, the Bellman functions are approximated by Benders cuts whose parameters are derived from the primal and dual information of the one-stage SDDP optimization problem at stage $t + 1$. As the algorithm progresses backward, the cuts' parameters are calculated (e.g., at stage $t + 1$) and then passed to the next stage (e.g., stage t). When the algorithm reaches the first stage, a forward simulation phase is carried out to check that the approximation of F_{t+1} is acceptable. If it is not, then a new backward optimization phase is implemented to refine the approximation. This iterative procedure is repeated until the values of Z^* obtained at the end of both the backward optimization phase and the forward simulation phase are statistically identical.

[22] For river basins where the dominant uses are hydropower generation and irrigated agriculture, the one-stage benefit function b_t includes three terms: (1) the benefits from the production of hydroelectricity, (2) the benefits from the irrigation sector, and (3) penalties for not meeting various operational and/or institutional constraints (e.g., minimum flow requirements, minimum water withdrawals for domestic uses). The benefits from the irrigation sector are only observed at the end of the irrigation season when crops are harvested and sold; the other benefits/penalties are observed all year round. The decision vector $\mathbf{x}_t$ now includes the outflow through the turbines $\mathbf{r}_t$, the outflow through the spillway $\mathbf{l}_t$, and the irrigation withdrawals $\mathbf{i}_t$. In a backward moving algorithm like SDDP, considering the agricultural benefits requires the inclusion of an additional state variable representing the volumes of water diverted to the irrigation schemes from the beginning of the irrigation season until current stage t. More details on the representation of the irrigation sector in SDDP is given in Appendix A. With this additional state variable denoted $\mathbf{y}_t$, the one-stage SDDP equation becomes

$$F_t(\mathbf{s}_t, \mathbf{q}_{t-1}, \mathbf{y}_t) = \max_{\mathbf{x}_t} \quad \{b_t(\mathbf{s}_t, \mathbf{q}_t, \mathbf{s}_{t+1}, \mathbf{r}_t, \mathbf{y}_t) + \alpha_{t+1} F_{t+1}\}. \quad (6)$$

[23] The main constraints are:

[24] Water balance equations:

$$\mathbf{s}_{t+1} - \mathbf{C}^R(\mathbf{r}_t + \mathbf{l}_t) - \mathbf{C}^I(\mathbf{i}_t) + \mathbf{e}_t(\mathbf{s}_t, \mathbf{s}_{t+1}) = \mathbf{s}_t + \mathbf{q}_t, \quad (7)$$

where $\mathbf{C}^R$ and $\mathbf{C}^I$ are the connectivity matrices representing the topology of the system (including irrigation return flows), and $\mathbf{e}_t$ is the vector of evaporation losses.

[25] Lower and upper bounds on storage:

$$\underline{\mathbf{s}}_{t+1} \leq \mathbf{s}_{t+1} \leq \overline{\mathbf{s}}_{t+1}. \quad (8)$$

[26] Limits on reservoir releases:

$$\underline{\mathbf{r}_t} \leq \mathbf{r}_t \leq \overline{\mathbf{r}_t}. \quad (9)$$

[27] Limits on irrigation water withdrawals:

$$\underline{\mathbf{i}}_t \leq \mathbf{i}_t \leq \overline{\mathbf{i}}_t. \quad (10)$$

[28] Update the volume of water diverted to the irrigation schemes:

$$\mathbf{y}_{t+1} - \epsilon\, \mathbf{i}_t = \mathbf{y}_t, \quad (11)$$

where ϵ is the vector of irrigation efficiencies. Here the dual variables (Lagrange multipliers) correspond to the at-site marginal water values for irrigated agriculture.

[29] Lower and upper bounds on dummy irrigation reservoirs:

$$\underline{\mathbf{y}}_{t+1} \leq \mathbf{y}_{t+1} \leq \overline{\mathbf{y}}_{t+1}. \quad (12)$$

[30] Approximation of the hydropower production functions:

$$\begin{cases} \hat{\mathbf{P}}_t - \psi^1 \mathbf{s}_{t+1}/2 - \omega^1 \mathbf{r}_t \leq \delta^1 + \psi^1 \mathbf{s}_t/2 \\ \vdots \\ \hat{\mathbf{P}}_t - \psi^H \mathbf{s}_{t+1}/2 - \omega^H \mathbf{r}_t \leq \delta^H + \psi^H \mathbf{s}_t/2, \end{cases} \quad (13)$$

where H is the number of planes that approximate the true hydropower functions, ψ, ω, δ, and ψ are the parameters derived from the corresponding convex hulls [*Goor et al.*, 2011] using the following procedure. It starts with the discretization of the feasible domain of the storage s and the release r of each hydropower station, and the calculation of the true hydropower function $P(s, r)$ at each grid point. Then $\hat{P}(s, r)$, which is an upper bound of $P(s, r)$, is estimated through a convex hull approximation by piecewise linear functions of the storage and turbining. The calculation of the convex hull $\hat{P}(s, r)$ at the grid points $P(s, r)$ corresponds to the smallest convex set that contains these points. It relies on the quick hull algorithm developed by *Barber et al.* [1996]. Because the convex hull overestimates the true hydropower production function, the parameters are adjusted so as to minimize the difference between the true production function and the piecewise linear approximation. This procedure is implemented in the preprocessing phase of the SDDP algorithm.

[31] Approximation of the benefit-to-go function F_{t+1}:

$$\begin{cases} F_{t+1} - \varphi^1_{t+1}\mathbf{s}_{t+1} - \eta^1_{t+1}\mathbf{y}_{t+1} \leq \gamma^1_{t+1}\mathbf{q}_t + \beta^1_{t+1} \\ \vdots \\ F_{t+1} - \varphi^L_{t+1}\mathbf{s}_{t+1} - \eta^L_{t+1}\mathbf{y}_{t+1} \leq \gamma^L_{t+1}\mathbf{q}_t + \beta^L_{t+1}, \end{cases} \tag{14}$$

where L is the number of cuts, and φ_{t+1}, γ_{t+1}, η_{t+1}, and β_{t+1} are cut parameters calculated during the backward optimization phase, from the primal and dual information available at stage $t + 1$ [*Tilmant et al.*, 2008].

[32] After convergence, the model provides a variety of results at key locations throughout the basin such as reservoirs, irrigation demand sites, power stations, river reaches: the turbined outflows, spills, storage levels, irrigation withdrawals, irrigation return flows, evaporation losses, river discharges, marginal water values (both at-source and at-site), net benefits/costs, deficits/surpluses, etc. Note that the at-source and at-site marginal water values correspond to the dual variables, also called Lagrange multipliers, associated with the mass balance equations (7) and (11), respectively. The dual variables give the change in the system's operational benefits due to a marginal change in the availability of water where the water balance is computed. These variables are automatically calculated when the optimization problem (6)–(14) is solved. Since many simulations are carried out, it is possible to trace out the empirical statistical distribution for each result.

2.4. Development and Management Scenarios

[33] To assess the benefits forgone due to unilateral irrigation developments, the stochastic hydro-economic model (6)–(14) is implemented on two different scenarios representative of two future management paths. In a first scenario, priority is given to the agricultural sector. Water for the agricultural sector is considered here as a "static" asset; a fixed volume of water is diverted to the irrigation schemes independently of both their productivity and the hydrologic status of the system. This scenario mimics a situation where riparian countries would be able to unilaterally develop their own irrigation projects regardless of the downstream impacts.

[34] In the second scenario, the optimization-based hydroeconomic model allocates water to its most productive use, assuming a complete coordination and cooperation among riparian countries. This scenario therefore considers that a central authority (e.g., a river basin authority) allocates water so as to maximize the basin-wide benefits derived from the river. The rationale for this scenario is that an economically efficient allocation can be perceived as a condition to the development of a benefit sharing mechanism; a user could not reject the benefit sharing mechanism on the grounds that more benefits could be reaped (and thus shared). In other words, we make the assumption that the size of the pie must first be maximized before users agree to share it. This second allocation scheme is called "dynamic" in contrast to the "static" scheme used in the first scenario.

[35] Note that both scenarios share the same river basin network with the same irrigation demand sites and the same hydropower plants. As explained latter, the network includes existing irrigation schemes and power stations, as well as the infrastructure and projects that are in an advanced planning stage. In other words, the river basin network is expected to represent the system at some point in a relatively distant future (beyond 2040 for our case study).

[36] For each scenario, the hydroeconomic model determines the optimal allocation policies, which means, for scenario 2, the reservoir releases and the irrigation withdrawals. For scenario 1, the model only provides the release policies since the irrigation withdrawals are imposed on the system and modeled as mathematical constraints, which will be met as long as there is enough water at the diversion site. The comparison between scenarios 1 and 2 will provide the benefits forgone (opportunity cost) for the entire basin system should the priority be given to the irrigation sector.

2.5. The Zambezi River Basin

[37] The Zambezi river basin covers an area of 1.37 million km^2 and is shared by eight countries (Angola, Zambia, Zimbabwe, Mozambique, Tanzania, Namibia, Botswana, Malawi), as illustrated in Figure 2. The total river length is 3540 km, making it the longest river discharging into the Indian Ocean.

[38] The river rises in the Kalene hills in northwest Zambia. It has many tributaries and, in Mozambique, the delta is distinguished by a wide, flat, marshy area with extensive floodplains. The river has three distinct stretches: the Upper Zambezi from its source to Victoria Falls, the Middle Zambezi from Victoria Falls to Cahora Bassa (a large man-made reservoir) which includes the major tributary the Kafue River, and the Lower Zambezi from Cahora Bassa to the delta.

[39] The headwater river system in the Upper Zambezi, which drains the Northern Highlands and the Central Plains of the North Kalahari Basin, is fed by rainfall concentrated during the December–January period. As the river flows south, it captures runoff from tributaries originating from Angola. After re-entering Zambia, the Zambezi River meanders through the Barotse plain, a large floodplain capable of storing up to 8.5 km^3 during the peak flow season. After flowing south, the river turns east and spreads again in a large swampy area (the Chobe Swamps), then flows east until it plunges over 98 m at Victoria Falls.

[40] The Middle Zambezi drains the area between Victoria Falls and the Cahora Bassa reservoir in Mozambique. Immediately downstream Victoria Falls, the Zambezi flows through a deep incised valley until it reaches the Kariba reservoir. The Kariba dam, closed in 1958, has a 180 km^3 reservoir and a 1275 MW hydropower plant. This dam has greatly altered the flow regime of the Zambezi. As the river continues to flow east, it receives runoff from a series of tributaries, the largest ones being the Kafue, which drains the Zambian copperbelt, and the Luangwa, which drains the eastern part of Zambia. After the confluence of the Zambezi and the Luangwa, the river enters the Cahora Bassa reservoir in Mozambique.

[41] The Cahora Bassa dam was constructed to supply a 2075 MW hydropower plant. The reservoir, with a storage capacity of 77 km^3, has also modified the flow regime (the monthly outflows are nearly constant throughout the year) [*Tilmant et al.*, 2010]. Slightly after Cahora Bassa, the river runs southeast toward the Indian Ocean. Before reaching the ocean, the river receives runoff from various tributaries

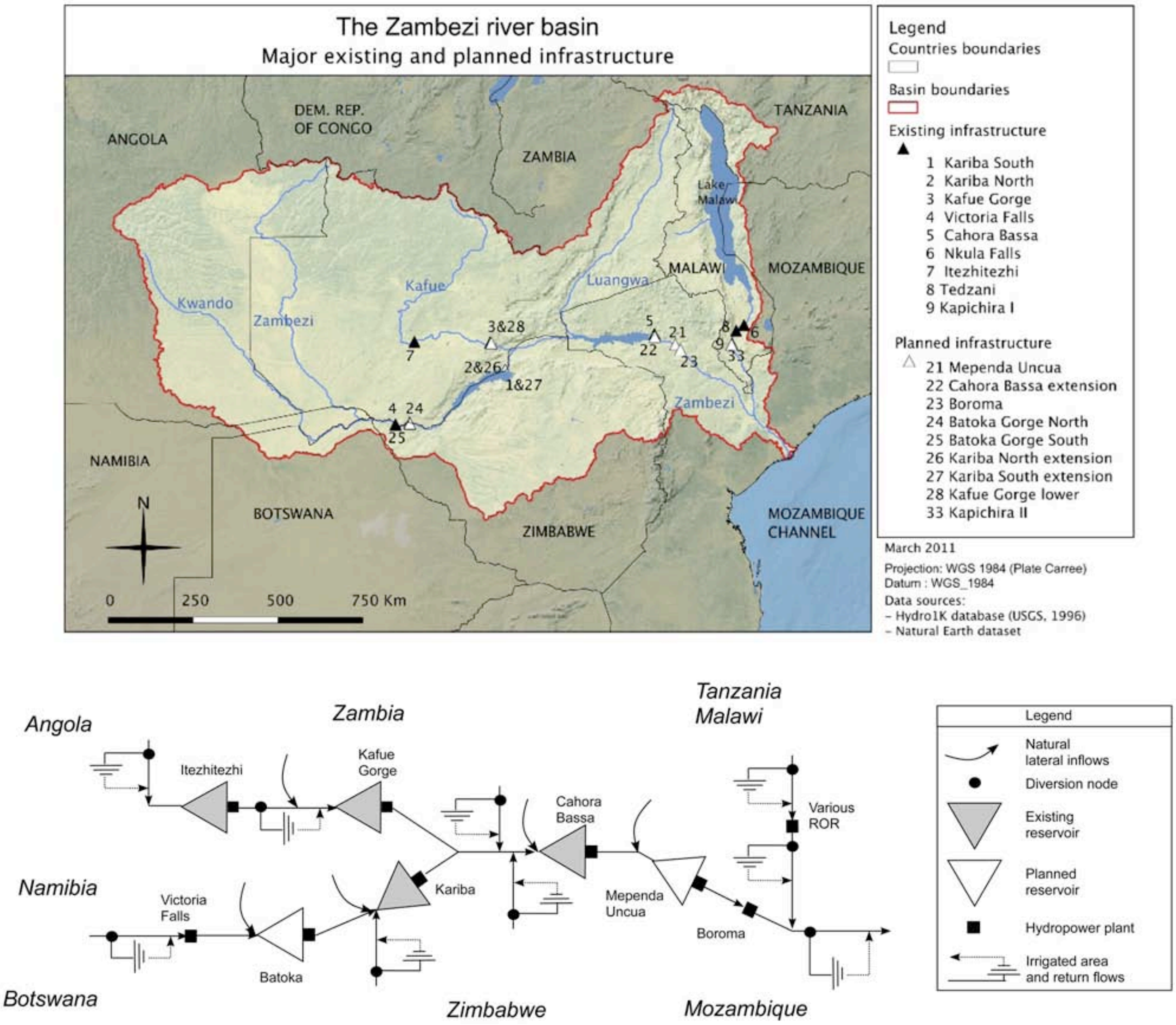

Figure 2. The Zambezi River basin and the schematization of the system.

including the Shire flowing from Lake Malawi. It then flows through a series of floodplains until is spreads out into the delta.

[42] Both scenarios described in section 2.4 consider existing and planned hydropower plants in the system, expected future water requirements for municipal and industrial uses, as well as existing and planned irrigation schemes. Figure 2 shows the map and the schematization of the Zambezi River basin. We can see that the topology is fairly complex: irrigation demand sites are distributed over the entire basin, therefore interfering with the power stations, which are found on the main stem of the Zambezi, the Kafue, and the Shire. The proposed methodology to assess the cost of noncooperation captures the complexity of the topology thanks to the use of a hydroeconomic model that can handle spatially distributed water projects. Table 1 lists the main characteristics of these infrastructure, while Table 2 gives the number of hectares that are currently irrigated and that could potentially be irrigated in each riparian country [*The World Bank*, 2008]. Typical annual crop water requirements (CWR) for various regions in the Zambezi basin are taken from *Denconsult* [1998], which were derived from CROPWAT/CLIMWAT [*Allen et al.*, 1998] for specific cropping patterns (Table 3). We assume that the cropping patterns will essentially remain the same in the future.

[43] The adopted modeling framework also assumes that a single institution is responsible for the planning and management of the Zambezi basin. At the time of writing, there is no such kind of institution. However, a new basin level institution called Zambezi Watercourse Commission (ZAMCOM) should be established when the Zambezi Watercourse Agreement will be signed and ratified by all riparian countries. As indicated earlier, Zambia refuses to sign and ratify the ZAMCOM Protocol on the grounds that the protocol does not adequately capture her contribution (more than 40%) to the Zambezi river. ZAMCOM's role would include among other things the preparation of basin development plans that would integrate the demands for the member countries.

[44] When dealing with large systems spread over several countries, data deficiencies are unavoidable. On the

Table 1. Major Dams and Hydropower Stations in the Zambezi Basin

Name	Country	Capacity (MW)	Existing (E) Planned (P)	Productivity (US$/1000 m^3)
Malawi	Nkula + Tedzani + Kapichira	279	E	17.88
Mozambique	Boroma	160	P	0.79
Mozambique	Mependa Uncua	1500	P	6.54
Mozambique	Cahora Bassa	2925	E + extension P	11.36
Zambia/Zimbabwe	Kariba	1980	E + extension P	10
Zambia	Itezhitezhi	120	P	4.27
Zambia	Kafue Gorge	1500	E + extension P	58.56
Zambia/Zimbabwe	Batoka Gorge	1600	P	15.95
Zambia	Victoria Falls	108	E	4

economics side, capital costs are ignored and considered as sunk costs. This assumption is motivated by the fact that the water allocation problem is essentially a midterm one since the capacity of the hydraulic infrastructure does not change over the planning period ($t = 1, 2, \ldots, T$). Recall that the management scenarios assume that all hydropower and irrigation infrastructure listed in Tables 1 and 2 have already been built. Consequently, their capital costs have already been expended, and it would not be correct to consider those costs when deriving the allocation policies as they cannot be changed by using the infrastructure or not (sunk cost fallacy). Moreover, the construction costs of much of these infrastructure are not yet known and will be financed through international donors; the opportunity cost of capital is therefore zero for the riparian countries. Finally, this study is not an ex-ante evaluation of the projects listed in Tables 1 and 2. Rather, it is an attempt at assessing the short-run economic consequences associated with the pursue of allocation policies resulting from a noncooperative development path, in which all the infrastructure have been built regardless of their basin-wide impacts.

[45] The economic valuation of water for hydropower requires that a value be assigned to the energy (MWh) produced by the hydropower plants. In this study, we assume that the average energy price is around 60 US$/MWh, which is the variable cost of a gas-fired power plant (a technology that is likely to be at the margin in the Southern African Power Pool where the contribution of coal-fired power stations is expected to decline in the coming decades as the share of other technologies gas and nuclear will increase). Values close to 60 US$/MWh were also adopted in the Master Plan for the Mozambican Power Sector released in 2009 and in the multisector investment opportunities analysis in the Zambezi basin [*The World Bank*, 2010].

[46] For the agricultural sector, detailed information required to assess the demand functions is not available for the entire river basin. For example, as a consequence of decreasing returns to scale, demand functions usually have a downward slope. Here, considering the data deficiencies, demand functions are horizontal, meaning that the marginal and average water values are identical. The water values are derived from three different gross margins: 300, 500, and 800 US$/ha, which are representative of low, average, and high agricultural productivities found for subsistence and smallholder farmers [*The World Bank*, 2008]. Note that gross margins around 800 US$/ha have been recently calculated in Zambia in 2008 when commodity prices were high [*Stephens*, 2008]. The gross margin corresponds to the value of product minus the variables costs (recall that capital costs are omitted). For example, a gross margin of 300 US$/ha corresponds to an average water value of 50 US$/1000 m^3 when 6000 m^3 of water is delivered at the farm plot. The two other values, 500 and 800 US$/ha, reflect increasing food prices and/or yields and are used to analyze the sensitivity of the results to these changes (Table 4). On the hydrologic side, our modeling framework can capture the variability, the spatial, and short-term (seasonal) temporal persistence of river discharges throughout the two basins, but not the presence of multiyear cycles nor climate change. The latter could in principle be modeled should time series of monthly discharges throughout the basin be available for different climate change scenarios.

[47] Finally, time series of monthly discharges are required at the entry points of the river basin network depicted in Figure 2. They are needed to generate the 50 hydrologic sequences used in the hydroeconomic model to capture the stochasticity of the hydrologic conditions across the Zambezi basin. These 50 sequences are generated by a built-in periodic autoregressive model with cross-correlated residuals whose parameters must be estimated from time series of historical natural discharges. These times series were provided by Dr. R. Beilfuss or derived from the Global Runoff Data Center (GRDC, World Meteorological Organization). *Beilfuss and dos Santos* [2001] carried out an extensive hydrological study of the Zambezi to reconstruct the historical time

Table 2. Irrigated Areas

Country	Existing Areas (ha)	Planned Extensions (ha)
Angola	1,989	20,000
Botswana	4	40,000
Malawi	43,987	163,000
Mozambique	11,211	49,000
Namibia	139	15,000
Tanzania	9,070	15,000
Zambia	34,016	117,600
Zimbabwe	70,850	45,360
Total	171,266	464,960

Table 3. Crop Water Requirements

Country/Region	CWR (m^3 ha^{-1})
Mozambique (Delta)	7690
Mozambique (Tete)/Zimbabwe	4910
Malawi/Tanzania (Shire)	7430
Zambia (Luangwa)	4700
Zimbabwe (Kariba)	8060
Zambia (Kafue)	8050
Upper Zambezi	4660

series at key locations in the basin using statistical analysis techniques. Historical monthly inflows over 30 years could have been used in simulation but it was decided to increase the number of sequences in order to get finer empirical statistical distributions of the results. The number of sequences is a trade-off between the representativeness of the stochastic process that generates the inflows and computation time.

3. Analysis of Simulation Results

[48] For each scenario, simulations are performed using the benefit-to-go functions F_t obtained during the last backward phase of the SDDP algorithm and synthetic hydrological sequences generated by a built-in periodic autoregressive model with cross-correlated residuals. Note that all scenarios exploit exactly the same hydrologic sequences. Historical flow records could have been used in the simulation phase, but due to the limited length of concurrent flows at all stations, we chose to work with artificial sequences. The planning horizon corresponds to ten years ($T = 120$) and simulation results are analyzed for year five only. This corresponds to a "steady state" condition which avoids the initial hydrological and storage conditions and the "end-effect" distortion due to the reservoirs' depletion that happens as the end of the planning period approaches [*Tilmant and Kelman*, 2007].

[49] As mentioned above, the most interesting simulation results are the turbined outflows, spills, storage levels, irrigation withdrawals, and the marginal water values (the dual variables associated with the mass balance equations). Since many simulations are carried out, it is possible to trace out the empirical statistical distribution for each result and for each scenario.

[50] The comparison between the total benefits obtained with scenarios 1 and 2 provides an estimate of the opportunity cost associated with unilaterally designed irrigation projects in the Zambezi basin. Since fixed costs are ignored and considered as sunk in both scenarios, the comparison will provide a short-run estimate. This cost will be proportional to the differences between the annual entitlements (scenario 1) and the volumes effectively withdrawn from the river system (scenario 2). Let X be the opportunity cost and $F(x) = P(X \leq x)$ be the cumulative distribution function, which gives the nonexceedance probability associated with x. Based on this definition, the complementary cumulative distribution function $1 - F(x)$ will thus give the risk of exceeding a particular cost x. Because this risk originates from the natural variability associated with the hydrologic conditions, the complementary cumulative distribution function provides a relationship between the stochastic variable (here the opportunity cost X) and the hydrological risk. Figure 3 displays the complementary cumulative distribution function $1 - F(x)$ of the short-run opportunity cost in the Zambezi basin. We can see that the average cost will be around 350 million US$/a. During dry years, with low exceedance probabilities, the cost can be as high as 600 million US$/a. It is also interesting to note that during wet years, the cost is negligible.

[51] The comparison of this opportunity cost with the overall annual benefits generated in the basin reveals the degree of suboptimality, and indirectly the level of commitment of existing resources. In the Zambezi, the opportunity cost corresponds to 10% of the average annual benefits (3.5 billion US$/a) and involves 2.36 km^3/a of water transfers, i.e., 75 m^3 s^{-1}, which is less than 30% of the average evaporation losses from the three largest reservoirs (7.8 km^3/a), and only 2% of the average Zambezi discharge into the ocean (4.155 m^3 s^{-1}).

[52] We can see in Figure 3 that the opportunity cost increases with the dryness of the system and thus with the exceedance probabilities. As the system gets dryer, the opportunity cost increases while the total benefits tend to decrease as there is less water in the system. To capture the relationship between the opportunity cost, the annual benefits, and the hydrologic variability, we have calculated the risks associated with increasing opportunity cost-benefit ratios as listed in Table 5. For example, for a 5% ratio (the proportion of the opportunity cost relative to the annual

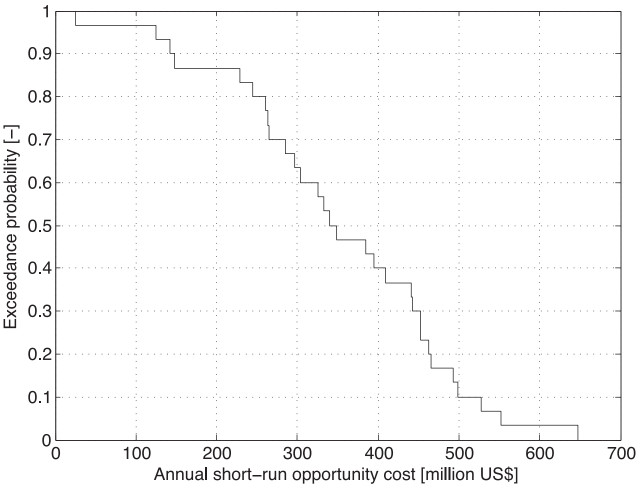

Figure 3. Cumulative distribution function. Opportunity cost.

Table 4. Development and Management Scenarios

Scenario	Allocation Scheme	Energy Price US$/MWh	Net Agricultural Margin US$/ha
1	Static	60	300
2	Dynamic	60	300
Variants			
2-med	Dynamic	60	500
2-high	Dynamic	60	800

Table 5. Hydrological Risk of Opportunity Cost/Benefit Ratios

Opp. Cost/Benefit (%)	Risk (%)
2.5	97
5.0	90
7.5	74
10.0	50
12.5	26
15.0	10
17.5	2.7
20.0	0

Table 6. Relative Sectoral Gains (Losses) (%) Associated With Economic Efficient Allocation

Country	Hydropower	Irrigation
Angola	0	−43
Botswana	0	−43
Malawi	0	0
Mozambique	8.5	0
Tanzania	0	0
Zambia	12.5	−66
Zimbabwe	10	−6

benefits is 5%), the hydrological risk of exceeding that ratio would be around 90%. If the ratio increases to 10%, the risk of exceedance would be 50%, i.e., one year out of two.

[53] The distribution of the economic gains and losses varies from country to country. In general, with scenario 2 (economic efficient allocation), upstream countries see their irrigation entitlements reduced, while the production of energy increases throughout the basin (from the upstream country to the outlet) (Table 6). Upstream countries also tend to face intersectoral trade-offs. In the Zambezi, Zambia would have to forgo two thirds of her irrigation projects for a 12.5% gain in energy (while at the same time contributing to much of the 8.5% increase in energy benefits observed in downstream Mozambique where the installed capacity would be around 4585 MW).

[54] Without some form of compensation (or benefit sharing mechanism), upstream countries will have little incentive to move toward a cooperative framework. In the Zambezi, Angola and Namibia, two countries located in the Upper Zambezi without large-scale hydropower projects, would have to forgo about 40% of their irrigation projects should downstream countries choose to exploit their hydropower potential. Hence, these two countries would be net losers due to the combined effects of natural resource endowment and investment decisions taken by downstream riparian countries.

[55] As indicated in section 2.5, the SDDP model was also run for two other agricultural productivities reflecting increasing food prices and/or yields. As the net margin in the agricultural sector increases, more water can be diverted to the irrigation schemes and the opportunity cost decreases. So do the upstream-to-downstream water transfers. For a net margin of 500 US$/ha, the average opportunity cost becomes 98 million US$/a, which is only 3.2% of the annual benefits. With a net margin of 800 US$/ha, the opportunity cost is negligible with less that 0.5% of the annual benefits. Table 7 provides an overview of the performance of the river system for the two scenarios and their variants with medium and high agricultural productivities (500 and 800 US$/ha, respectively).

4. Conclusions

[56] Throughout much of the African continent, nations have embarked on a new hydraulic mission, trying to secure as much water resources as possible in order to meet their sustained demands for food and energy. The new role played by emerging countries on the world stage has provided developing countries with an alternative source of financing, and a leverage in their relations with Western donors and their strict environmental and social standards. This new race to control water resources might be costly in the long term, economically and politically. In this study we have attempted to assess the economic cost of noncooperation in international river basins where the dominant uses are irrigated agriculture and hydropower generation. Since irrigation projects are likely to be more controversial, the cost of noncooperation is defined as the benefits forgone when water is allocated to the agricultural sector regardless of its productivity. Hydropower generation, on the other hand, is essentially nonrival since the existing and planned reservoirs provide the power companies with some form of flexibility and independence. This was illustrated with the Zambezi River basin, one of the largest river basins in Africa for which we expect major developments in the coming decades. The analysis of simulation results reveals that the benefits forgone due to unilaterally developed irrigation projects would cost, on average, 10% of the total benefits in the Zambezi if the gross margin in irrigated agriculture is on the low side. However, if the investments are targeted to more productive irrigation schemes, the cost of noncooperation becomes negligible and the risk of exceeding a given proportion of the opportunity cost would be significantly reduced (provided that energy prices remain constant). On the other hand, the fact that the distribution of the gains and losses among riparian countries is not equitable

Table 7. Annual Performance of the Different Scenarios and Their Variants

	Scenario 1	Scenario 2	Scenario 2-Med	Scenario 2-High
Opp. cost (million US$/a)	0	351	98	22
Opp. cost/benefits ratio (%)	0	10.1	3.16	0.5
Water withdrawals (cms)	335	260	317	340
Energy (TWh/a)	53.05	58.82	54.51	53.26
Average cultivated area (ha)	621.210	476.244	575.175	612.213
		Risk of exceedance (%)		
Opp. cost/benefit ratios (%)		Scenario 2	Scenario 2-med	Scenario 2-high
2.5		97	56	36
5.0		90	35	21
7.5		74	18	10
10.0		50	7	5
12.5		26	2	2
15.0		10	0.6	0.5
17.5		3	0	0
20.0		0	0	0

is a major obstacle toward the efficient sharing of existing water resources in this basin. It also stresses the importance of developing adequate benefit sharing mechanisms if one wants to turn the riparian countries away from a *fait accompli* policy. The methodology could be extended to include environmental damages due to a lack of coordination should relevant information be made available.

Appendix A: Representation of the Irrigation Sector in SDDP

[57] Recall that the one-stage benefit function b_t in SDDP includes three terms: (1) the benefits from the production of hydroelectricity, (2) the benefits from the irrigation sector, and (3) penalties for not meeting various operational and/or institutional constraints. It is not possible in SDDP to directly incorporate irrigation benefits into the one-stage benefit function because they are neither additive nor independent from previous decisions, i.e., irrigation withdrawals. Instead, irrigation benefits I are only be observed at the end of the irrigation season (stage $= t_f$) provided that both the timing and volume of water delivered to the crops during the irrigation season are adequate. This appendix explains how benefits from the irrigation sector are modeled in a backward moving algorithm like SDDP.

[58] Let $\zeta_{t_f}^{d,p}$ be the net benefit function for crop p at the irrigation demand site d. The benefits from the entire irrigation sector are given by

$$I_t = \begin{cases} \sum_d \sum_c \zeta_{t_f}^{(d,p)} & \text{if} \quad t = t_f \\ 0 & \text{if} \quad t \neq t_f. \end{cases} \tag{A1}$$

[59] The net benefit function $\zeta_{t_f}^{(d,p)}$ associated with crop p at site d is calculated by

$$\zeta_{t_f}^{(d,p)} = [\pi^{(d,p)} c^{(d,p)} - \theta^{(d,p)}] A^{(d,p)}, \tag{A2}$$

where $\pi^{(d,p)}$ (US\$/T) and $\theta^{(d,p)}$ (US\$/ha) are, respectively, the farm gate price and the production costs of crop p at site d, while $A^{(p,d)}$ (ha) is the maximum area that can be cultivated for that crop at that site, and $c^{(d,p)}$ (T/ha) is the actual yield.

[60] To assess the impact of variation in supplies on crop yields, a linear relationship between crop yield deficit and the actual evapotranspiration (ET_a) is also used [*Allen et al.*, 1998]:

$$c^{(d,p)} = \overline{c}^{(d,p)} \left[1 - K_y^{(p)} \left(1 - \frac{ET_a^{(d,p)}}{\overline{ET}^{(d,p)}} \right) \right], \tag{A3}$$

where

$c^{(d,p)}$ (T/ha) is the actual yield,
$\overline{c}^{(d,p)}$ (T/ha) is the maximum yield,
ET_a (mm) is the actual evapotranspiration,
$\overline{ET}$ (mm) is the maximum evapotranspiration,
$K_y^{(p)}$ (–) is the crop yield coefficient.

[61] In SDDP the ratio between the actual and maximum evapotranspiration is approximated by

$$\frac{ET_a^{(d,p)}}{\overline{ET}^{(d,p)}} \approx \frac{y_{t_f}^{(d,p)}}{\overline{y}_{t_f}^{(d,p)}}, \tag{A4}$$

where $\overline{y}_{t_f}^{(d,p)}$ is the maximum volume of water that can be delivered to crop p at site d throughout the entire irrigation season, from stage t_i until stage t_f, and $y_{t_f}^{(d,p)}$ is the volume of water effectively allocated to that crop at that site. With this approximation, $y_t^{(d,p)}$ becomes a new state variable modeled as a "dummy" reservoir that is being refilled during the irrigation season (see equation (11)) and depleted at the end of that season (stage t_f) when crops are harvested and sold (Figure 4). Constraints imposed on irrigation withdrawals at stage t (see equation (10)) make sure that the allocation decisions are consistent with the crop water requirements at that stage and with the capacity of the conveyance system.

[62] As one can see, incorporating the irrigation benefits into the objective function increases the dimension of the optimization problem since additional dummy reservoirs

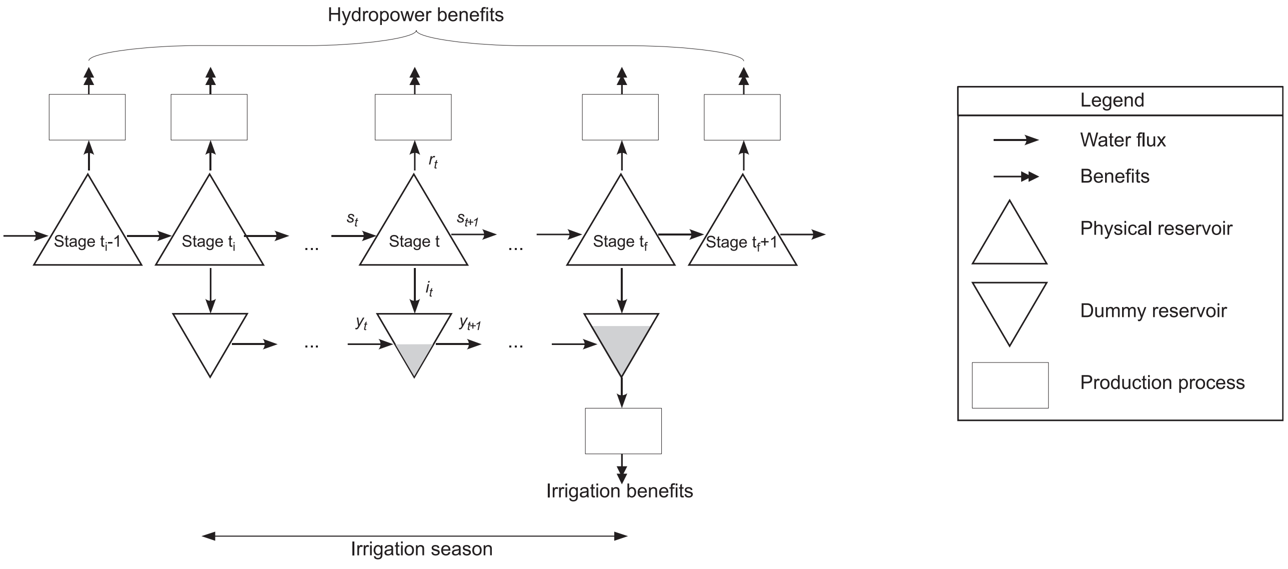

Figure 4. Dummy reservoir of accumulated water for irrigation.

must be included in the state vector. The SDDP model of the Zambezi has nine irrigation reservoirs and six hydroelectric ones (the other power stations are run-of-the-river ones). The SDDP algorithm can handle such a large state space by constructing a locally accurate solution to the optimization problem through sampling and function approximation.

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