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Restoring a flow regime through the coordinated operation of a multireservoir system: The case of the Zambezi River basin

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[1] Large storage facilities in hydropower-dominated river basins have traditionally been designed and managed to maximize revenues from energy generation. In an attempt to mitigate the externalities downstream due to a reduction in flow fluctuation, minimum flow requirements have been imposed to reservoir operators. However, it is now recognized that a varying flow regime including flow pulses provides the best conditions for many aquatic ecosystems. This paper presents a methodology to derive a trade-off relationship between hydropower generation and ecological preservation in a system with multiple reservoirs and stochastic inflows. Instead of imposing minimum flow requirements, the method brings more flexibility to the allocation process by building upon environmental valuation studies to derive simple demand curves for environmental goods and services, which are then used in a reservoir optimization model together with the demand for energy. The objective here is not to put precise monetary values on environmental flows but to see the marginal changes in release policies should those values be considered. After selecting appropriate risk indicators for hydropower generation and ecological preservation, the trade-off curve provides a concise way of exploring the extent to which one of the objectives must be sacrificed in order to achieve more of the other. The methodology is illustrated with the Zambezi River basin where large man-made reservoirs have disrupted the hydrological regime.

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1. Introduction

[2] The intersectoral allocation of water is becoming more and more challenging as the demand for water increases due to population growth and improving living standards. In river basins where large storage facilities provide the flexibility to transfer water in space and time, improving the operational effectiveness of those infrastructures has become increasingly important. This need intensified following the publication of the World Commission on Dams report [*World Commission on Dams* (*WCD*), 2000], which concluded that many large storage facilities worldwide have failed to meet their expected performance, due to the lack of attention devoted to the operational aspects once the storage project is completed. The issue of poor performance is exacerbated when considering new environmentally orientated objectives, such as environmental flow requirements, that were historically overlooked in the project development and licensing phases [*Brown and Watson*, 2007]. Moreover, existing reservoir operating policies are often developed for individual projects, without considering potential synergies with other infrastructures present in the same basin [*Labadie*, 2004].

[3] With the water storage reservoirs that often accompany hydropower development, multiple complementary benefits may also occur including water supply (municipal, industrial and agricultural), flood control and recreational opportunities. However, alongside these benefits well-known detrimental effects are evident, including impoundment of free-flowing river habitat, blockage of fish migration and reduced water quality in reservoirs and downstream river reaches [*Acreman and Dunbar*, 2004]. Related to these direct effects, other impacts include the interruption of flooding regimes and geomorphological processes that maintain aquatic habitat diversity downstream, which are required to sustain healthy riverine ecosystems [*Jager and Smith*, 2008]. From healthy ecosystems comes a plethora of ecosystem goods and services including floodplains, wetlands, and slack water habitats, which in turn provide such services as fish spawning grounds, fertile agricultural land, and natural flood attenuation; all of which are of direct benefit for human systems and requirements. Flows are crucial for keeping these ecosystems in a healthy state, for example regular inundation of floodplains provides nutrient rich sediment that contributes toward fertile soils. Through research, scientists have identified that preserving some components of the hydrological characteristics of a flow regime is key to aquatic ecosystem

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functions [see, e.g., *Dunbar and Acreman*, 2001], and these components include: magnitude, variability, duration, and timing. Downstream of regulated infrastructures like hydropower plants, these natural components of flow are often missing. *Suen and Eheart* [2006], for example, address this issue of restoring the main components of a flow regime downstream of a dam and provide a trade-off relationship between human needs and ecological flow regime maintenance. *Harman and Stewardson* [2005] present a simulation model to assess the operating rules of a single dam to meet environmental flow targets expressed as base flow and pulse targets.

[4] In recent years there has been a growing consensus amongst water professionals and the public, which reflects the greater understanding of the linkage between flow and ecology, that states that the environment must be considered as a legitimate water user, whose demand must be balanced with that of the uses considered traditionally [*Davis*, 2007]. However, incorporating the environmental benefits into the decision-making process requires first that the environmental processes are adequately understood and also that the subsequent benefits are estimated. To achieve the latter, economists have developed and implemented various non-market valuation techniques for water resources management problems [*Loomis*, 2000], especially in the field of water quality such as stream and wetland restoration [*Collins et al.*, 2005; *Woodward and Wui*, 2001]. Environmental valuation attempts to estimate the economic value, in monetary terms that members of society receive from uses of natural resources which cannot be efficiently allocated through markets due to their public good characteristics. Although there is little consensus among economists on the meaning and use of environmental valuation in policy [*Shabman and Stephenson*, 2000], it is generally acknowledged that the role of valuation in water resources allocation is more meaningful when marginal changes in (re)allocation decisions are envisaged [*Turner et al.*, 2003]. Moreover, the contribution of environmental valuation must be seen as offering a common metric showing how environmental and traditional uses contribute to society, rather than the exact monetary values it provides.

[5] Due essentially to data and cost constraints, wetland valuation studies usually provide a range of values, which can sometimes be fairly large with a difference of one order of magnitude between the lower and upper limits. Besides this uncertainty, the majority of wetland valuation studies also tend to underestimate the economic value of wetlands since some of the non-use values, like the existence and bequest values, are difficult to monetize and are thus often ignored [*Turner et al.*, 2000]. Another difficulty comes from the fact that wetland valuation studies produce aggregated values corresponding to a particular environmental state, instead of marginal values, which are more relevant for problems involving marginal changes in water allocation. Assuming that decreasing marginal returns to scale is the rule for wetlands, the use of average values would overestimate the value of the wetland. One of the challenges arising from the above considerations is to exploit the results of those wetland valuation studies to determine basin-wide allocation policies and assess a trade-off curve between hydropower generation and ecological preservation. In this paper, simple demand curves for environmental goods and services are constructed for a range of possible wetland values, and then used in a hydro-economic model to determine the corresponding release policies for the different reservoirs in the basin. Performance indicators for the hydropower and environmental objectives are then estimated from simulation results, and used to trace out the trade-off curve between hydroelectric production and ecological preservation.

[6] The reallocation of water from the hydropower sector to the environment in the Zambezi Basin will be used to illustrate the methodology. In that basin, large reservoirs and hydropower stations have altered the hydrological regime and disrupted the ecosystems [*Gammelsrod*, 1996]. *Timberlake* [2000] indicates that the existing dams already pose a risk to particular areas in the basin including the Kafue flats (downstream of Ithezitezi dam), Middle Zambezi floodplains (downstream of Kariba), and the Lower Zambezi floodplains and delta (downstream of Cahora Bassa) where the main users and concerns were identified as ranging from small-scale agriculture, coastal and freshwater fisheries to biodiversity and public health interests.

[7] Implementing hydropower-to-environment water transfers in the Zambezi requires the development of new reservoir operating policies that should help restoring degraded ecosystems in the lower Zambezi without undue adverse impacts on hydropower generation. The latter is a critical issue considering that much of the energy generated in the Basin can be exported to neighboring countries through the Southern African Power Pool (SAPP). To achieve this goal, the reservoir operating policies are optimized for three different management scenarios: the first scenario focuses on hydropower generation and neglects environmental benefits; the second and third scenario rather seek to maximize basin-wide benefits by restoring a flow regime in the Zambezi delta through either a high-value or a low-value environmental flow release. The multireservoir operation problem is solved using Stochastic Dual Dynamic Programming (SDDP), an algorithm that can handle a large number of reservoirs and stochastic inflows [*Tilmant and Kelman*, 2007; *Tilmant et al.*, 2009].

[8] This paper is organized as follows: section 2 provides an overview of the optimization model. Section 3 describes the Zambezi River basin and the multireservoir system. The SDDP model for the Zambezi basin is described in section 4. Simulation results are then analyzed in section 5, which is then followed by conclusions.

2. Stochastic Dual Dynamic Programming

[9] The hydropower operation problem can be mathematically represented as a multistage, stochastic, nonlinear optimization problem. In stochastic dynamic programming (SDP), a technique well suited to solve such problems, release decisions r_t are made to maximize current benefits f_t plus the expected benefits from future operation, which are represented by the recursively calculated benefit-to-go function F_{t+1}:

$$F_t(s_t, h_t) = \underset{q_t|h_t}{E}[\max\{f_t(s_t, q_t, r_t) + \underset{h_{t+1}|h_t,q_t}{E} F_{t+1}(s_{t+1}, h_{t+1})\}] \quad (1)$$

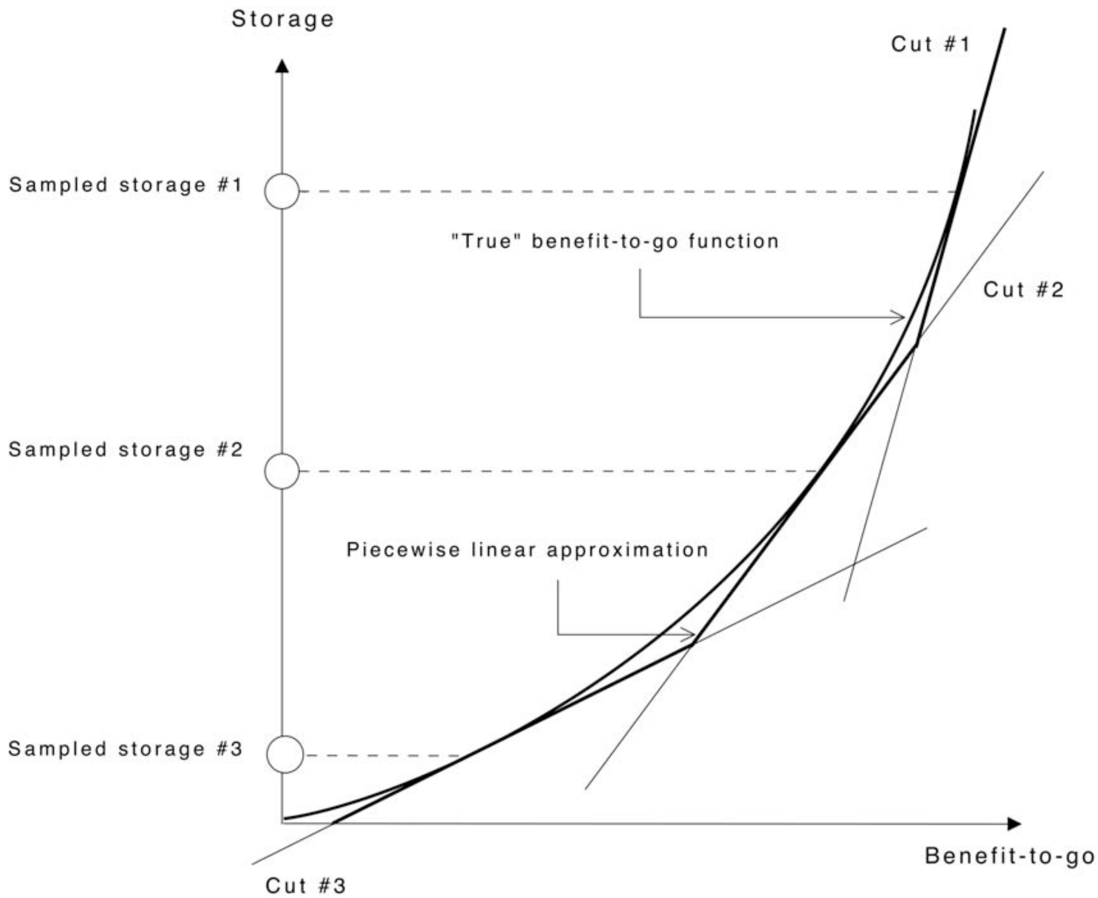

Figure 1. Piecewise linear approximation of F_{t+1}.

[10] As we can see in equation (1), the vector of state variables typically includes the storage level s_t at the beginning of time period t, and a hydrologic variable h_t representing various hydrologic information. $\underset{q_t|h_t}{E}$ denotes the conditional expectation operator for flow q_t given the hydrologic information h_t. *Tejada-Guibert et al.* [1995] and *Kim and Palmer* [1997] discuss the various options for the hydrologic state variable h_t. To solve the hydropower operation problem with SDP, the state variables must be discretized so that an approximate solution of SDP can be developed by evaluating the functional equation at the grid points only. The drawback of this discrete approach comes from the fact that the computational effort required to solve the SDP model increases exponentially with the number of reservoirs, making it unsuitable to handle systems involving more than 3–4 reservoirs [*Johnson et al.*, 1993]. Although SDP could in principle be used to solve the optimization problem in the Zambezi (the number of existing reservoirs is four), we prefer to work with stochastic dual dynamic programming (SDDP), an extension of the traditional discrete stochastic dynamic programming (SDP) that can handle much larger state-spaces. This is because (i) SDDP is much more efficient in terms of computation time and (ii) future work will look at a larger optimization problems including existing and planned reservoirs and hydropower plants.

[11] The basic idea behind SDDP is the construction of a locally accurate approximation of the benefit-to-go function. This is done through sampling and decomposition; for each sampled value of the state variables a hyperplane is constructed and provides an outer approximation of the benefit-to-go function. These hyperplanes are equivalent to Benders cuts in Benders decomposition [*Kall and Wallace*, 1994]. Intuitively, the computational effort should be reduced since the value of F_{t+1} can now be derived by extrapolation instead of interpolation as in SDP. In other words, a limited number of values for the state variables (points) are now sufficient to provide an approximation of F_{t+1} as illustrated in Figure 1.

[12] To further save computation time the SDDP algorithm first starts with a small number of points and then recursively constructs the cuts corresponding to these points starting at the last stage T and moving backward until the first stage t_0. The cuts generated during this backward optimization phase are then evaluated by checking whether the approximation they provide is statistically acceptable or not. This is done by simulating forward the system with (1) the cuts generated in the previous backward optimization phases and (2) several hydrologic sequences, which can be historical and/or synthetically generated. If the approximation is not acceptable, then a new iteration starts and a new backward optimization phase is implemented with a larger sample which now also contains the points the last simulation went through.

[13] In SDDP, the structure of the one-stage optimization problem (1) is particular: it must be a convex program, such

as a linear program (LP), so that the Kuhn-Tucker conditions for optimality are necessary and sufficient. In particular, the gradient of the objective function is equal to the linear combination of the gradients of the binding constraints and their corresponding dual information. Moreover, the hydrologic state variable is typically a vector of p previous flows q_{t-1}, q_{t-2},., q_{t-p}, which are then used to generate q_t using a built-in periodic autoregressive model PAR(p) with cross-correlated residuals. From these restrictions on the mathematical structure of the one-stage optimization problem, it is possible to evaluate the derivatives of the objective function F_{t+1} with respect to the state variables (s_{t+1}, q_t) from the derivatives of the binding constraints and the dual information, which are both available at the optimal solution at stage $t + 1$. Details concerning the analytical determination of the gradients of the functional equation F_{t+1} is given by *Tilmant et al.* [2008].

[14] When dealing with hydropower systems, the one-stage optimization problem (1) is not convex because the production of hydroelectricity is a nonlinear function of the head (storage) and release variables. One way to remove this source of nonconvexity is to assume that the production of hydro-electricity is dominated by the release term and not by the head (or storage) term [*Archibald et al.*, 1999; *Wallace and Fleten*, 2003]. This assumption is valid as long as the difference between the maximum and minimum heads is small compared to the maximum head. Recently *Goor et al.* [2009] presented a methodology that removes this assumption by constructing a piecewise linear approximation of the true hydropower production function through convex hulls. This methodology is summarized below.

[15] Let $P_t(j)$ be the power produced by hydropower plant j during period t and H be the number of linear approximations of the true hydropower production function. The h^{th} hyperplane is defined as:

$$\hat{P}_t - \psi^h s_{t+1}/2 - \omega^h r_t \leq \delta^h + \psi^h s_t/2 \tag{2}$$

where $\hat{P}_t$ is the $(1 \times J)$ vector of approximated power generated during time period t; ψ^h, ω^h and δ^h are the $(J \times 1)$ vectors of parameters; s_t and s_{t+1} are the $(1 \times J)$ vectors of the beginning-of-period and end-of-period storages respectively; r_t is the $(1 \times J)$ vector of releases during period t.

[16] To calculate the parameters ψ^h, ω^h and δ^h of the piecewise linear approximations of the hydropower function, one must first discretized the feasible domain of storage and release. For each combination of these state and decision variables (s_u, r_v), $u = 1$,., U and $v = 1$,., V, the true hydropower function $P(s, r)$ is calculated. Then, $\hat{P}(s, r)$ is estimated through a convex hull approximation by piecewise linear functions of storage and turbining. The convex hull $\hat{P}(s, r)$ associated with the grid points $P(s, r)$ is the smallest convex set that contains the points. It relies on the very efficient Quick Hull algorithm developed by *Barber et al.* [1996] and freely available from http://www.qhull.org. The calculation of these parameters is done during the preprocessing phase of the SDDP algorithm.

3. Zambezi River Basin

[17] The focus area for the study is the Zambezi basin which has a catchment area of 1.39 million km^2 and is located in south east Africa (Figure 2). The river rises in the Kalene hills in north-west Zambia and flows through nine riparian countries along its 2750 km length, before outfall into the Indian Ocean in Mozambique. 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 which includes the major tributary the Kafue River, and the Lower Zambezi from Cahora Bassa to the delta.

[18] Four main dams exist on the Zambezi; the Kariba dam (1959) and the Cahora Bassa (filled 1974) are both located on the main stem with an installed capacity of 1350 MW and 2075 MW respectively. The other two are located on the Kafue River, only one of which has hydroelectric capacity. The Kafue dam has an installed capacity of 900 MW while the Itezhitezhi acts as a storage dam, collecting water for the Kafue dam. Both the Kariba and Kafue dams are currently being upgraded and significant work is underway toward planning new infrastructures in the basin. Table 1 lists the main characteristics of the dams.

[19] Many studies have been undertaken on the ecology and associated ecosystems of the Zambezi River basin and according to *Timberlake* [2000] the existing dams pose a risk to particular areas in the basin including the Kafue flats (upstream of Kafue Gorge dam), Middle Zambezi floodplains (downstream of Kariba), and the Lower Zambezi floodplains and delta (downstream of Cahora Bassa). This paper focuses particularly on the delta area downstream of Cahora Bassa, where several studies have been conducted on the environmental flow requirements [*Beilfuss and Brown*, 2006; *Beilfuss*, 2001a, 2001b].

[20] According to *Beilfuss and Brown* [2006], current flows to the delta have become reasonably constant during the year with a mean annual post-regulation discharge of 3800 m^3/s. Reported bank-full discharges are of the order of 4500 m^3/s. For this paper a target pulse flow of 7000 m^3/s was chosen in the delta during the peak flow season in February and March. Providing this pulse flow during the wet season aims to restore part of the seasonal component of the flow regime, which is currently not evident in the data series. During pre-impoundment times, and therefore also pre-regulation, this seasonal flow was achieved 50% of the time in the delta. This flow results in total inundation of channel islands and floodplain areas within the upper diked perimeter, and widespread flooding along Cuacua channel of the delta north bank.

4. Hydro-economic Modeling of the Zambezi River Basin

[21] Generally speaking, hydro-economic models establish a link between supply and demand for water, taking into account spatially distributed hydrologic features, hydraulic infrastructures and water demands [*Booker and Young*, 1994; *Ward and Lynch*, 1996; *Harou et al.*, 2009]. The hydro-economic model used in this study on the Zambezi basin includes the existing largest infrastructures listed in Table 1 and only considers up to two main objectives depending on which scenario is analyzed: hydropower generation and ecological preservation. Allocation decisions, like reservoir releases, spills and end-of-period storages, are determined by the SDDP model which seeks to maximize the expected economic net benefits over a

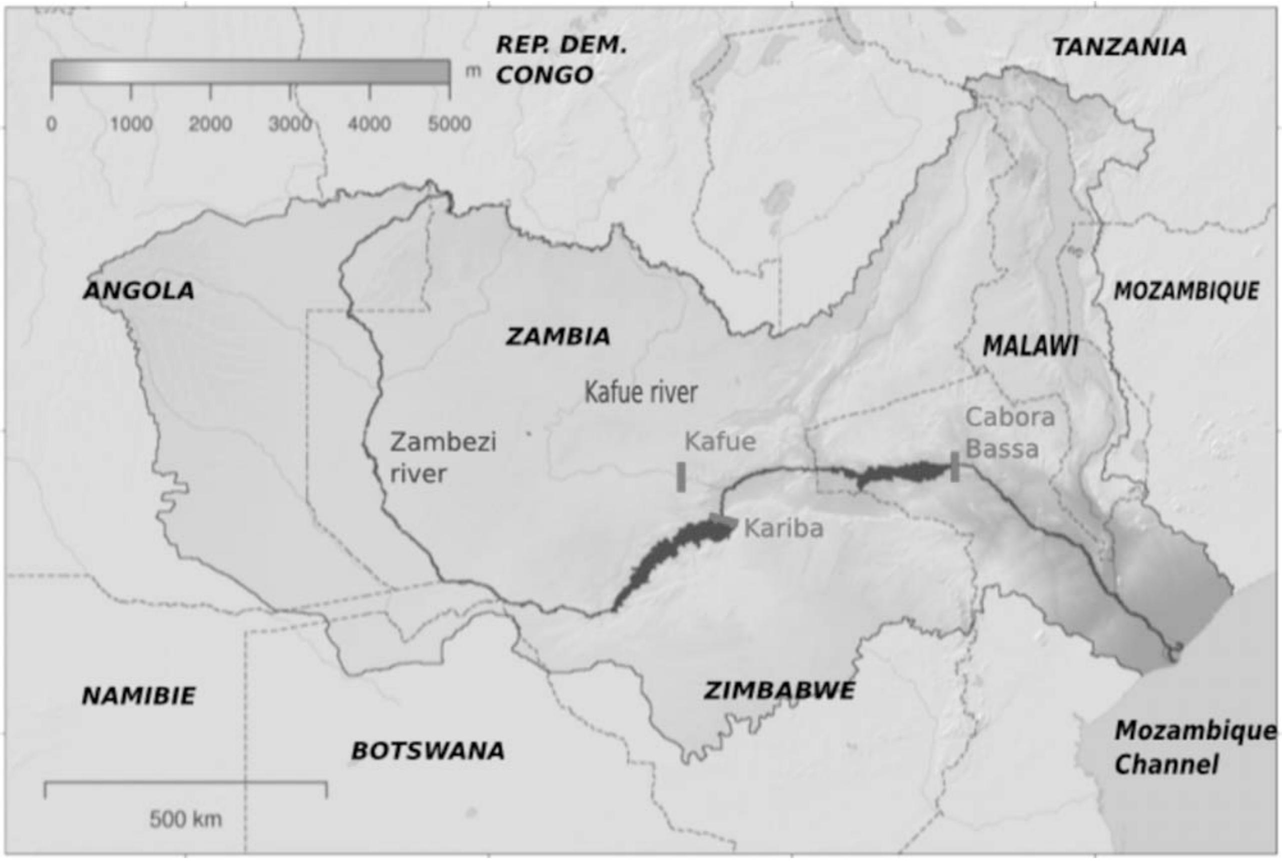

Figure 2. The Zambezi River basin.

given planning period. Our proposed stochastic hydro-economic modeling approach differs from the optimization model developed by *Gandolfi et al.* [1997] who used a deterministic formulation with a non-economic objective function to optimize the allocation decisions in the Zambezi basin.

[22] Due to the large over-year storage capacity of the Kariba reservoir, the planning period was defined as 120 months, while the number of SDDP simulation sequences is set to 50. In other words, the optimal reservoir operating policies calculated during the optimization phase of SDDP are simulated 50 times over a period of 10 years. Those 50 hydrologic sequences are generated by a built-in periodic autoregressive model with cross-correlated residuals whose parameters were estimated from time series of historical natural discharges available at key locations throughout the basin. Historical monthly inflows during 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 representativeness of the stochastic process that generates the inflows and computation time.

[23] To determine the reservoir operating policies with environmental flows in the delta, the hydro-economic model requires that a demand curve, also called marginal benefit function, for environmental flows be imposed at the delta. Integrating under this demand curve yields the benefits associated with the provision of environmental goods and services in the delta, which can then be combined with the benefits from hydropower generation, and maximized in SDDP. Because the one-stage optimization problem in SDDP must be formulated as a linear program, a demand curve must be stepwise so that the integration produces a piecewise linear function. This assumption means that the average and marginal water values are identical within each block (step). One alternative to the demand curve could be to remove the environmental flows from the objective function and treat them as additional constraints like those of *Gandolfi et al.* [1997]. The lower bounds, i.e., the minimum flow requirements, could then be changed in order to trace out the trade-off relationship between environmental flows and energy generation.

[24] The few environmental valuation studies carried out in the Zambezi basin attempt to assess the total economic value of goods and services associated with Zambezi's wetlands independently of the hydrologic (supply) conditions [*Turpie et al.*, 1999; *Seyam et al.*, 2001]. In other words, they do not provide demand functions, which are value/scarcity sensitive and are essential to the study of supply demand relationships. We circumvented this lack of information by

Table 1. Major Existing Dams in the Zambezi Basin

Name	Identification	Capacity (MW)	Live Capacity (km^3)
Kariba	Ka	1320	65
Itezhitezhi	Ii	0	5
Kafue Gorge	Ke	900	1.1
Cahora Bassa	Ca	2075	44

Table 2. Scenarios

Scenario	Wetland Value (US$/ha)	Water Value, Delta (US$/1000 m^3)	Energy Value (US$/MWh)
Base Case	0	0	80
EF1	1000	34	80
EF2	100	3.4	80

constructing simple, discrete, demand curves with only two blocks: in the first block, ranging from 0 to 7000 m^3/s (target peak flow), water has a constant (positive) value reflecting scarcity. Beyond that target flow, water is no longer valuable; extensive flooding of lowlands and channels occur so that the marginal value of water becomes negligible. Note that there is no conceptual difficulty to consider more blocks, and even blocks with negative values if the corresponding flows lead to flood damages, but that information was not available for this study and very large flows are already attenuated by the existing dams.

[25] As pointed out by *Woodward and Wui* [2001] and *Brander et al.* [2006], the range of estimates derived from wetland valuation studies is quite large, with typical values in Africa ranging from 100 US$/ha to 1000 US$/ha, while typical values in the Zambezi are closer to the lower bound. These two extremes are the starting point to design two scenarios: in EF1 the multireservoir system will be managed taking into account a high-value environmental flow where the water value in the first block is set to 34 US$/1000 m^3; in scenario EF2, the water value in the first block is reduced to 3.4 US$/1000 m^3, which corresponds to a low-value environmental flow. The water values in the first block were derived from the value of wetlands (ranging between 100 to 1000 US$/ha), the delta area (1.2 million ha) and the target flow (7000 m^3/s) over the peak flow season (February and March).

[26] These simple demand curves with only two blocks are similar to the traditional cost-based penalty functions used in many reservoir studies where the economic costs (benefits) are assumed to be minimized (maximized) at some ideal storage levels and/or discharges [*Lund and Ferreira*, 1996; *Watkins and Moser*, 2006]. From this assumption, any deviation from these target levels incurs some costs and must be penalized in the objective function. However, as pointed out earlier, the model can accommodate demand curves with more blocks which, we hope, will be filled with more accurate data once the future wetland valuation studies will be completed throughout the basin.

[27] The EF1 and EF2 scenarios will be compared to a situation where environmental uses are ignored and the multireservoir system operated for hydropower generation only (Base Case scenario). The comparison between the three scenarios will reveal the extent of hydropower-to-environment water transfers when two different environmental flow scenarios are considered: a high-value (34 US$/1000 m^3) and a low-value one (3.4 US$/1000 m^3). The fundamental aim here is not to put the exact dollar value on environmental flows but to see the marginal changes in allocation policies when different economic values of those flows are included in the analysis.

[28] The economic valuation of water for hydropower requires that a value be assigned to the energy (MWh) produced by the hydropower plants. Since the hydropower-to-environment water transfers involve marginal changes in hydroelectric power production, the value of energy is best captured by the alternative cost of generating energy. In a well-functioning power pool, the alternative cost is usually the market price. Here, we assume that generators are price takers; their output does not affect the market price in the Southern African Power Pool (SAPP). Trading in the SAPP is organized around two market mechanisms: long term Power Purchase Agreements (PPA) and the Short Term Energy Market (STEM). Historically, the PPA mechanism was the only form of trading with contracts typically lasting for 10–15 years. Due to excess capacity in the early 90ies, the agreed prices in the SAPP have been well below the long run marginal costs. However, as a result of growth in regional demand combined with the deferral of new generation investments the SAPP has been running short of

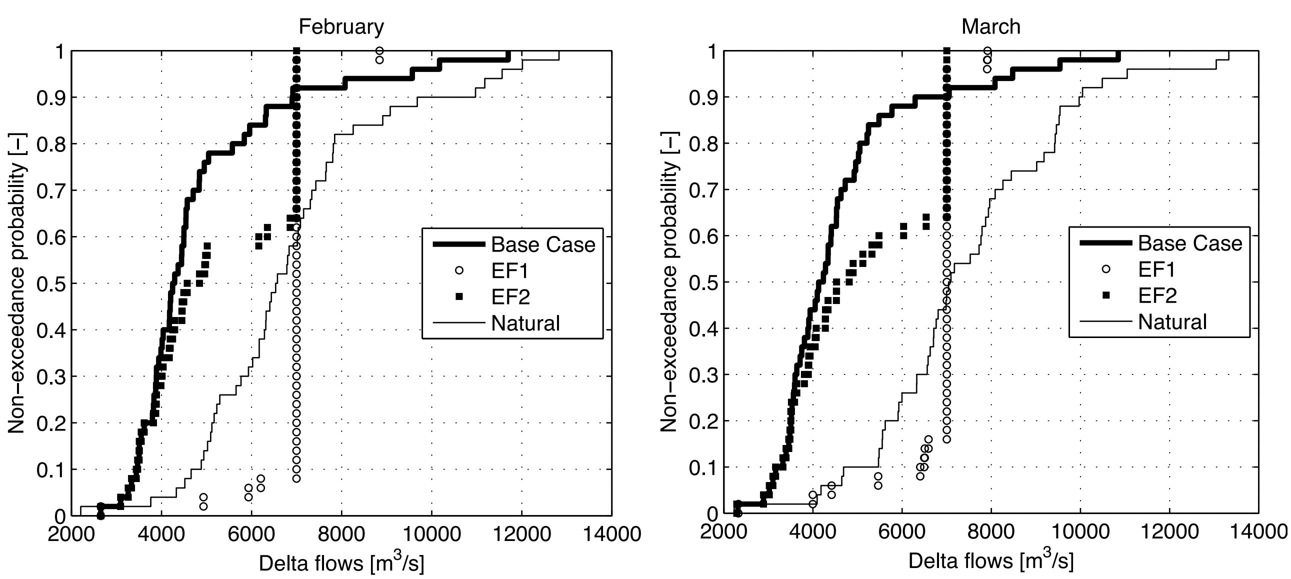

Figure 3. Cumulative distribution functions of monthly river discharges in the delta in February and March.

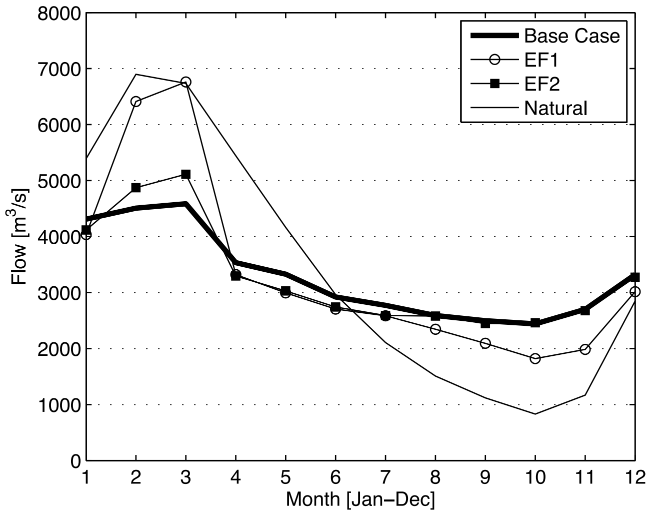

Figure 4. Average monthly discharges in the delta for the three scenarios: Base Case, EF1 and EF2.

energy for some years. In this study, we assume that energy prices are around 80 US$/MWh, which corresponds to the variable cost of a diesel-fired power plant. Table 2 lists the main characteristics of the three scenarios.

5. Analysis of Simulation Results

[29] The simulation results corresponding to the three management scenarios described above are compared. Figure 3 displays the statistical distributions of river discharges in the delta for the two critical months, February and March. These distributions give the probability of non-exceedance (Y axis) for any particular river flow in the delta. Besides the statistical distributions of the three scenarios (Base Case, EF1 and EF2), Figure 3 also displays the distributions of the natural flows, i.e., without any regulation and evaporation losses in the reservoirs (Natural). As already pointed out by several authors, the examination of Figure 3 reveals that the presence of upstream reservoirs significantly lower Zambezi discharges in February and March; the statistical distributions Base Case are consistently to the left of the corresponding Natural distributions, with a difference of about 2000 m^3/s. In February, for instance, the median values of Natural and Base Case are 6500 and 4000 m^3/s respectively. Under pristine conditions, a flow of 4500 m^3/s would already be exceeded 90% of the time.

[30] When reservoir operating policies are determined with a high value assigned to the environmental flow (EF1), the target flow, which is of the order of 7000 m^3/s, can be met 90% and 85% of the time in February and March respectively. The reliability in meeting this target flow is reduced to 25% when a low value flow is considered (scenario EF2). In that case, the economic value attached to river discharges during the peak flow season is not sufficient to force the system to release more water downstream during dry years. Rather, the water is kept in storage for future uses, therefore contributing to augmenting low flows later during the dry season as illustrated in Figure 4. We can see that with the EF1 scenario, the average monthly discharges in the delta are identical to that of the Base Case scenario from August until December. The contrast between the dry and wet seasons is more pronounced when environmental flows are highly valued, with river discharges reaching their lowest values around November.

[31] The monthly river discharges in the delta can be disaggregated into three major components: the turbined outflows from Cahora Bassa, the spillage outflows from Cahora Bassa, and the contribution of mostly unregulated tributaries between Cahora Bassa and the delta such as the Shire River flowing from Lake Malawi (see Figure 2). Figure 5 displays the average contribution of these three components to the monthly flows in the delta for the Base Case and the EF1 scenarios. Increasing the peak discharge in the delta can only be achieved through larger spills from Cahora Bassa since the power station is already discharging at maximum capacity almost all yearlong. During the dry season, from August to November, turbined outflows are reduced in order to refill the reservoir and increase the head-on turbines.

[32] Downstream river discharges can be increased during critical wet months by changing the reservoir operating rules. While previous studies have been limited in scope, assessing the impacts only on Cahora Bassa, this study reveals that in fact one of the upstream reservoirs (Kariba) will be greatly impacted should the operation of the multireservoir system be coordinated. This emphasizes the need for a basin-wide approach to investigate the potential trade-off in a holistic manner. Lake Kariba will see larger fluctuations in storage levels and contribute differently to the flow downstream depending on the status of the system, i.e., storage levels and inflows: during dry years, Kariba can increase its releases in order to refill Cahora Bassa thanks to its huge

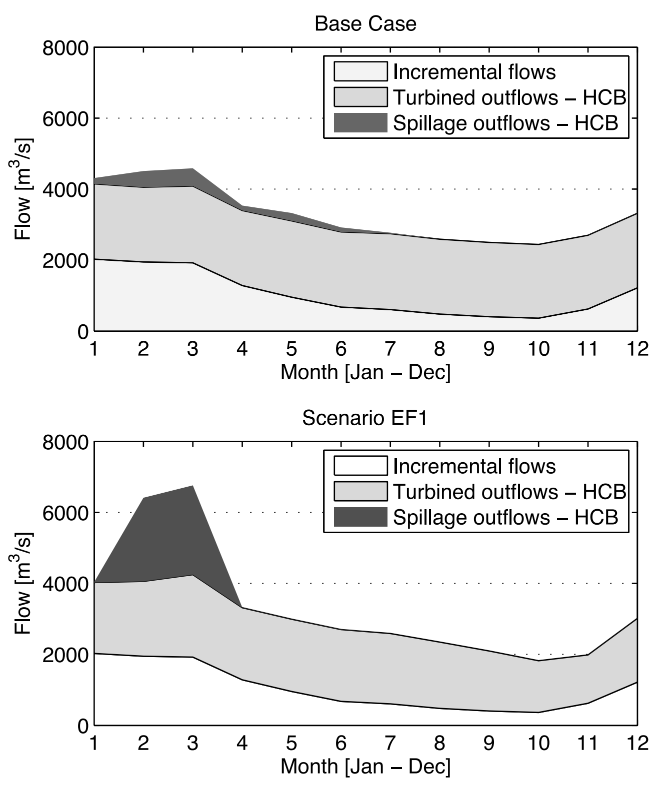

Figure 5. Flow separation in the delta for the Base Case and EF1 scenarios.

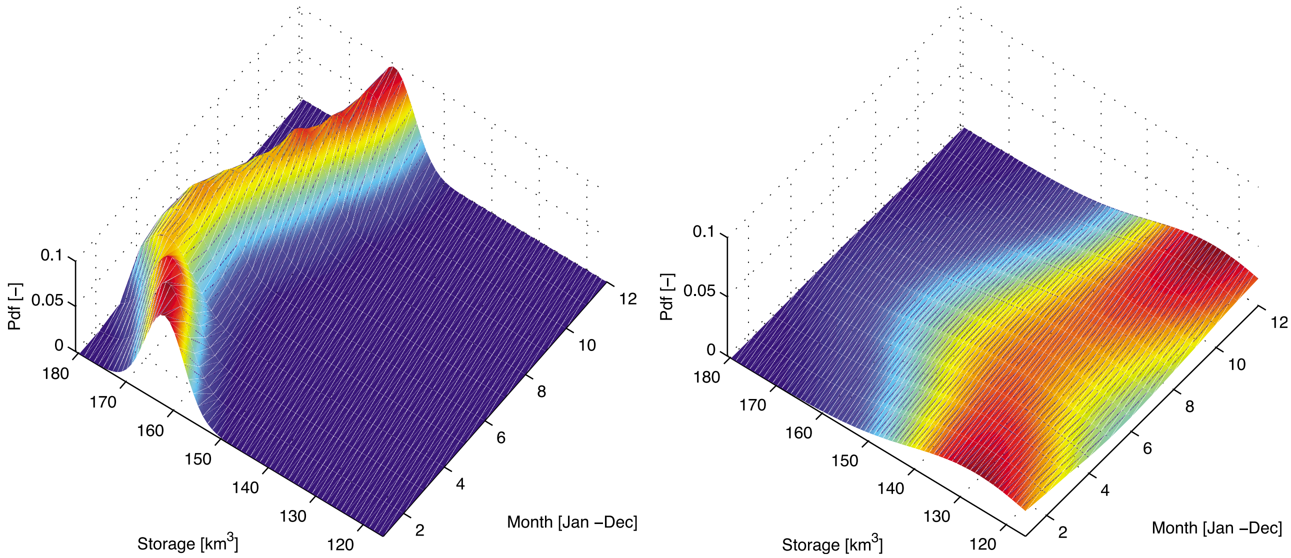

Figure 6. Probability density functions of storage volumes in Kariba for the (left) Base Case and (right) EF1 scenarios.

storage capacity, and allows Cahora Bassa to increase the total outflows to the delta. During wet years, this contribution is not needed and Kariba can keep a high pool elevation in order to maximize hydropower generation. This mechanism explains the difference between the simulated storage levels in the Kariba reservoir when environmental benefits are considered or not. Figure 6 shows the probability density functions of simulated monthly storage volumes in Kariba for the Base Case and EF1 scenarios respectively. We can see that the storage levels are lower with a larger variance under the EF1 scenario. Note that those lower storage levels also save evaporation losses (a reduction of 14% can be observed between Base Case and EF1 scenarios, roughly corresponding to 2% of the average annual Zambezi flow at Kariba).

[33] Implementing environmental flows in the delta will obviously reduce the power producers' flexibility, i.e., their ability to adjust power generation, and may also affect the amount of energy that can be generated by altering the drawdown refill cycle. The comparison between the three scenarios reveals that the implementation of reservoir operating policies that explicitly consider environmental benefits would reduce, on average, the annual energy output by 6% with scenario EF1, or by 1.4% when environmental flows have a low value (scenario EF2). Since we are unable to distinguish between average and marginal productivity of the wetlands due to data constraints, the overall precision of the total wetland values for different supply (hydrologic) conditions cannot be as high as we would like, and cannot be directly compared to the economic returns derived from hydropower generation. Table 3 lists the average annual energy generated by the three power stations in each scenario, while Figure 7 displays the corresponding cumulative distribution functions $F(X)$. We can see that when high-value environmental flows are implemented (EF1), the energy generated by the Zambezi system is not only lower but also more variable with a minimum of 19 TWh compared to about 27 TWh in the Base Case scenario. Note that the maximum hydroelectric production is unaffected by the implementation of environmental flow releases. This is because during wet years, the supply is such that there is no need to trade-off the release of

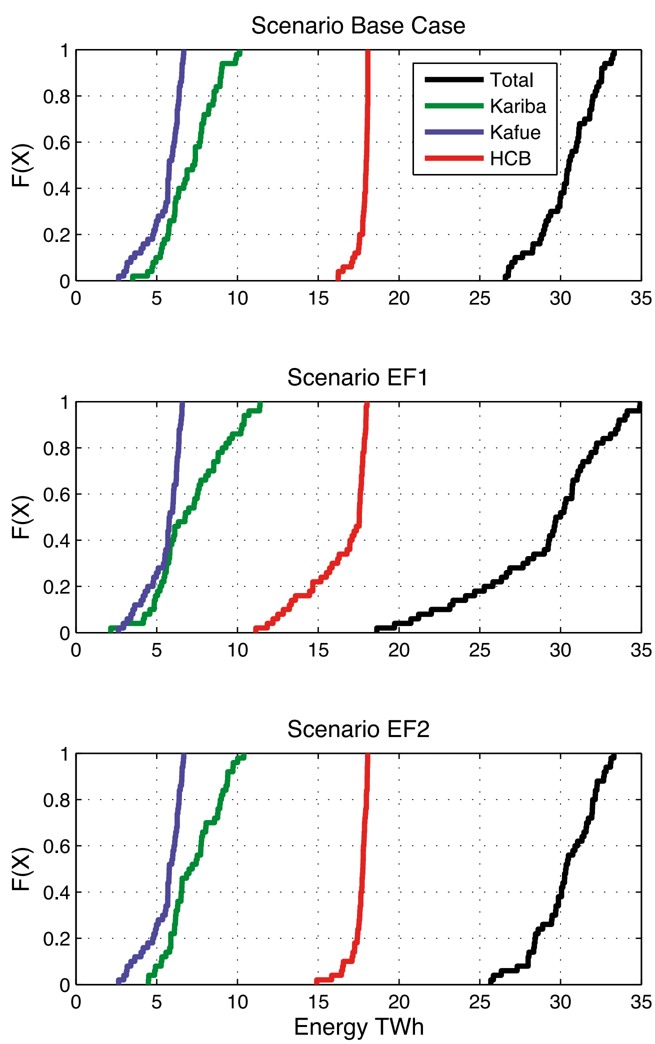

Figure 7. Cumulative distribution functions of energy generation: (top) Base Case, (middle) EF1 and (bottom) EF2.

Table 3. Average Annual Hydropower Generation[a]

Scenario	Kariba	Kafue	HCB	Total
Base Case	7.349	5.454	18.025	30.828
EF1	7.057	5.492	16.417	28.966
EF2	7.080	5.521	17.791	30.392

[a]Values are in TWh.

water against keeping it storage. Finally, in the Base Case scenario, the SDDP-derived average annual energy output (30.828 TWh) is similar to the expected production (30.9 TWh) as reported by *WCD* [2000], but much lower than the mean energy output calculated by *Gandolfi et al.* [1997] (34.1 TWh). Such a difference can be explained by the fact that deterministic formulations tend to overestimate the performance of the water resources system [*Philbrick and Kitanidis*, 1999].

[34] In the Base Case scenario, the production of Cahora Bassa (HCB) is fairly independent of the hydrologic conditions: an output of 17.5 TWh is already exceeded 85% of the time, while the maximum is 18.1 TWh. This is because much of the inflows into HCB are already regulated by upstream infrastructures. However, the production risk increases significantly under the EF1 scenario since 17.5 TWh is now exceeded only 55% of the time, i.e., roughly one year out of two. During dry years, the energy generated by HCB decreases rapidly as the reservoir is unable to refill and maintain a high head. HCB production reaches a low 11 TWh during the driest year, compared to 16.2 TWh in Base Case scenario.

[35] The production at Kariba is also more variable under the EF1 scenario: higher outputs in wet years compensate lower outputs observed during dry years. The average annual production of that power station in EF1 is thus only reduced by 4% as a result of lower heads on turbines (Kariba barely spills). The production at Kafue Gorge, on the other hand, is essentially unaffected by the provision of environmental flow releases; the differences between average energy generation in the three scenarios are less than 1%. This is mainly due to the fact that Kafue Gorge is the most productive power station in the system with an average productivity of 79 US$/1000 m^3, which must be compared to 14 US$/1000 m^3 (Kariba) and 22 US$/1000 m^3 (HCB). In addition, the contribution of the Kafue river to the Zambezi discharges in the delta is significantly lower than the flow going through Kariba.

[36] Figure 8 presents the relationship between firm energy and the risk of not exceeding certain discharges (4500, 6000 and 7000 m^3/s) in the delta during the peak flow season in February and March. The trade-off curve is obtained via the following steps.

[37] 1. Set the current economic value of wetlands in the delta (i.e., 0 US$/ha) and derive the corresponding demand curves.

[38] 2. Using SDDP, optimize and then simulate the operation of the system.

[39] 3. Calculate the firm energy (e.g. 95% reliability) and assess the hydrological risk for some key discharges in the delta (e.g., 4500, 6000 and 7000 m^3/s).

[40] 4. Increase the economic value of wetlands (e.g., 100, 400, 1000 US$/ha) and repeat steps 1, 2 and 3.

[41] 5. Plot the hydrological risk versus firm energy for the various critical flows in the delta.

[42] Figure 8 shows, in a concise way, the trade-off among the two main objectives (hydropower generation and environmental flows). More specifically, it shows the sacrifices in terms of reduced firm energy if society chooses to restore a flow regime downstream. For example, if a 5% reduction of firm energy were socially acceptable (from 27 to 25.65 TWh), then a 4500 m^3/s discharge in the delta could already be achieved or exceeded in February and/or March 70% of the time (hydrological risk of 30%), while the risk of not meeting 6000 and 7000 m^3/s would be around 40 and 55% respectively. Conversely, for any given hydrological risk and target discharge, one can find the corresponding firm energy. This kind of information is key to the overall

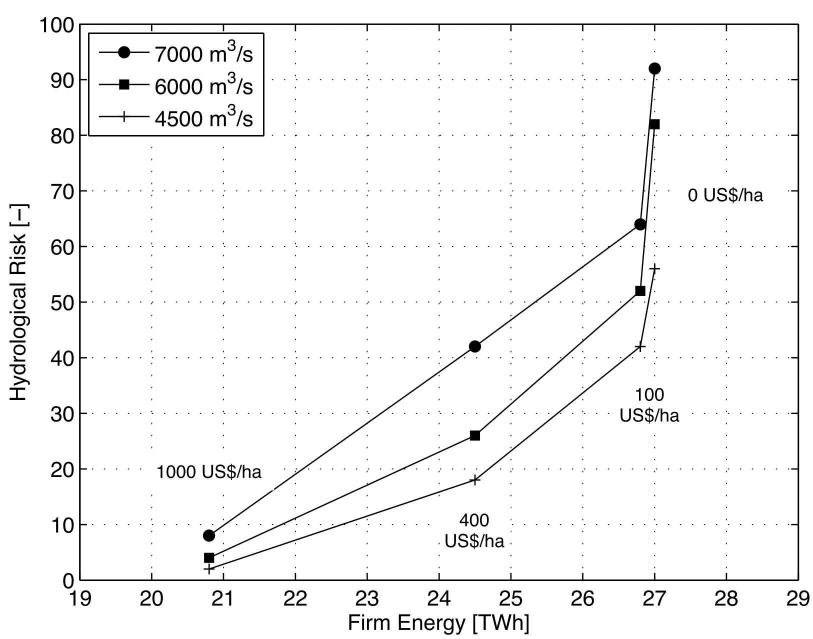

Figure 8. Trade-off curves between firm energy and hydrological risk in the delta.

environmental flow process since wetland conservation benefits cannot easily be made comparable with the returns derived from alternative uses (e.g., hydropower generation), especially in developing countries where comprehensive wetland valuation studies are rare.

6. Conclusions

[43] This study analyzes hydropower-to-environment water transfers in a water resources system with multiple reservoirs. The Zambezi River basin is used as a case study. Despite the assumptions, this study shows that the re-operation of existing reservoirs to meet new demands and restoring floods in the delta can be achieved through the coordinated operation of the multireservoir system, which in turn requires that adequate policies are in place to ensure coordination and share the corresponding benefits and costs. No conclusion can be drawn whatsoever as to the economic justification of implementing or not environmental flows in the Zambezi basin due to the unavailability of some data at the time of writing. In particular, it would be very useful to have wetland valuation studies that track site changes in values across different hydrologic conditions in order to draw more detailed and accurate demand curves for environmental goods and services. Also, there is no conceptual difficulty, within the modeling framework, to include the benefits from restored areas extending from the most upstream dams to the coast if the information were available. The delta is just one part of a much larger restored system that will return benefits and, provided that the timing is similar, including the economic returns from environmental flows in mid-reaches of the river will support the hydropower-to-environment water transfers throughout the basin.

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