Optimal Water Allocation in the Zambezi Basin

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Abstract: The Zambezi river basin is of utmost importance for the riparian countries in terms of energy, food production and natural resources. In 2030, the Zambezi river basin will support 80 million people and the population is expected to double within 30 years if current growth rates are maintained. This population growth will therefore lead to increasing water demands for food and energy, which may compete with ecological flows in environmentally sensitive areas. Even though there is no legal agreement on the sharing of Zambezi waters, we believe that an assessment of basin-wide economically efficient allocation policies will provide valuable information at a time where water managers and policy makers in the region are negotiating the establishment of a unified river basin institution called the Zambezi Watercourse Commission (ZAMCOM). That institutions would be responsible for, amongst other things, the design of allocation rules. In this study, basin-wide allocation policies are derived from an integrated, stochastic, hydro-economic model which considers the largest existing and planned hydraulic infrastructures and irrigation schemes in the basin. The model allocates water in space and time so as to maximize the net economic returns from both consumptive and non-consumptive uses over a given planning period. The analysis of simulation results reveal that most of the planned irrigation schemes in Zambia, Zimbabwe, Namibia, Angola and Botswana and not economically sound if the power stations that are in an advanced planning phase are implemented.

Keywords: Hydro-economic optimization; Hydropower; Irrigation; Environmental Flows

1 INTRODUCTION

The Zambezi river basin is of utmost importance for the riparian countries in terms of energy, food production and natural resources. In 2030, the Zambezi river basin will support 80 million people and the population is expected to double within 30 years if current growth rates are maintained. This population growth will therefore lead to exploding water demands for food and energy, which may compete with minimum flow requirements for environmentally sensitive areas. Since the construction of Kariba dam in the late 1950s, the river basin has experienced other infrastructure developments for energy generation, flood control, recreation, fishing and irrigation (see Table 1). The Zambezi river basin now hosts two large artificial reservoirs, Kariba and Cabora Bassa which store more than 200 billion m\(^3\) together, which is about six times the average annual flow at Victoria Falls and two times the average annual discharge flowing to the sea. Two other reservoirs can be found in the Kafue tributary: Ithezi-Tezhi and Kafue Gorge.

According to the FAO, the irrigation potential in the Zambezi river basin is more than 3 million ha, of which only 5% is already developed. If there is considerable scope for irrigation development to boost agricultural production, this may also negatively affect the production of hydroelectricity as less water will be available for the generators of the hydropower plants. With an installed...
capacity of more than 4,500 MW, hydropower generation is one of the major commercial uses of water, providing energy to Zimbabwe, Zambia, Mozambique and South Africa. The production of hydroelectricity also conflicts with the need to maintain ecological functions as it alters the hydrological regime downstream. Since the construction of Cabora Bassa, the productivity of fisheries, shrimp industry and floodplains has declined due to constant flows and the absence of flooding. Kariba and Cabora Bassa reservoirs also trap most of the sediment load of the upper and middle Zambezi, releasing essentially clear water downstream. This lack of sediments and the reduction in nutrients have resulted in major disruptions of the Zambezi's riverine, wetland, deltaic and coastal ecosystems, which could already be observed 10 years after the commissioning of Cabora Bassa.

Most of the major irrigation and hydropower projects on the drawing boards in the various riparian countries are being developed independently. In a hydropower-dominated river basin like the Zambezi, the opportunity cost associated with upstream withdrawals for irrigation purposes may be significant. As a matter of fact, the foregone hydropower generation from all power stations downstream of the consumptive use may become quite large, not to mention the reduction in flow discharges and their impacts on downstream ecosystems. Neoclassical economic theory advises allocating water to its most productive uses, thereby maximizing the productivity of the available water. In a system involving consumptive (irrigation) and non-consumptive (hydropower) users, a trade-off must be found at each stage between diverting, releasing and keeping the water in storage for future uses. The "temporal" trade-off, i.e. the balance between immediate and future uses, is achieved when the future and immediate marginal water values are equal. The release and withdrawal decisions give rise to a "spatial" trade-off: at a particular reservoir, the equilibrium between withdrawal and release is reached when the lateral productivity is identical to the sum of downstream productivities. What would therefore be the economically efficient balance between irrigated agriculture and hydropower generation in the Zambezi? Where water could be withdrawn for irrigation and what would be the optimal irrigated areas in the different countries taking into account the agro-meteorological heterogeneity of a large basin like the Zambezi, the stochasticity of supply (hydrology), the existing and planned hydropower projects, and the productivity of wetlands?

We attempt to answer these questions by formulating the allocation problem as an stochastic hydro-economic optimization problem, which is solved by an algorithm that belongs to the so-called approximate dynamic programming field [Powell, 2007]. The model seeks to maximize the sum of net benefits over a given planning period taking into account physical, economical and institutional constraints. The model, called stochastic dual dynamic programming (SDDP), provides statistical distributions of allocation decisions (withdrawals, reservoir releases, spills, storage volumes) and various economic information such as marginal water values, which can be used to analyze the performance of the system.

2 THE ZAMBEZI BASIN

The focus area for the study is the Zambezi basin which has a catchment area of 1.39 million km² and is located in south east Africa (Figure 1). The river rises in the Kalene hills in northwest Zambia and flows through nine riparian countries along its 2,750 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.

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 hydrotlectric capacity. The Kafue dam has an installed capacity of 900 MW while the Ittezhitezhi 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 towards planning new infrastructures in the basin. Table (1) lists the main characteristics of existing and planned dams.

Table 1: Major dams in the Zambezi basin

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Capacity</th>
<th>Existing (E)/ Planned (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boroma</td>
<td>Mozambique</td>
<td>160 MW</td>
<td>P</td>
</tr>
<tr>
<td>Mependa Uncua</td>
<td>Mozambique</td>
<td>1.500 MW</td>
<td>P</td>
</tr>
<tr>
<td>Cahora Bassa</td>
<td>Mozambique</td>
<td>2.925 MW</td>
<td>E + upgrade P</td>
</tr>
<tr>
<td>Kariba</td>
<td>Zambia/Zimbabwe</td>
<td>1.980 MW</td>
<td>E + upgrade P</td>
</tr>
<tr>
<td>Itzehitezhi</td>
<td>Zambia</td>
<td>120 MW</td>
<td>P</td>
</tr>
<tr>
<td>Kafue Gorge</td>
<td>Zambia</td>
<td>1.500 MW</td>
<td>E + upgrade P</td>
</tr>
<tr>
<td>Batoka Gorge</td>
<td>Zambia/Zimbabwe</td>
<td>1.600 MW</td>
<td>P</td>
</tr>
<tr>
<td>Victoria Falls</td>
<td>Zambia</td>
<td>108 MW</td>
<td>E</td>
</tr>
</tbody>
</table>

Table (2) lists the potential and existing irrigated areas per country in the Zambezi basin. As we can see, by 2030 the area under irrigation could increase by a factor of four, which would correspond to an addition of 20,000 ha per year over a period of 25 years. According to the World Bank [2008], the production of cereals is expected to be the main driver for this growth.

Table 2: Potential and existing irrigated areas (World Bank, 2008)

<table>
<thead>
<tr>
<th>Country</th>
<th>Potential area (ha)</th>
<th>Existing area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angola</td>
<td>16.109</td>
<td>1.989</td>
</tr>
<tr>
<td>Botswana</td>
<td>280</td>
<td>4</td>
</tr>
<tr>
<td>Malawi</td>
<td>169.520</td>
<td>43.987</td>
</tr>
<tr>
<td>Mozambique</td>
<td>91.166</td>
<td>11.211</td>
</tr>
<tr>
<td>Namibia</td>
<td>1.544</td>
<td>139</td>
</tr>
<tr>
<td>Tanzania</td>
<td>26.128</td>
<td>9.070</td>
</tr>
<tr>
<td>Zambia</td>
<td>227.458</td>
<td>34.016</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>141.226</td>
<td>70.850</td>
</tr>
<tr>
<td>Total</td>
<td>674.230</td>
<td>171.266</td>
</tr>
</tbody>
</table>

The main ecologically sensitive areas are the Kafue flats in Zambia, the Mana Pools, which is a World Heritage Site, in Zambia and Zimbabwe, the Barotse Plain in Zambia, and finally, the Zambezi delta in Mozambique. During pre-impoundment times, and therefore also pre-regulation, these wetlands were healthy ecosystems, shrinking and growing according to the natural flow regime. Nowadays, the large reservoirs and hydropower stations have altered the hydrological regime, degrading these fragile ecosystems [Gammelsrod, 1996]. This has triggered a series of studies to better understand the value of these wetlands [Turpie et al., 1999; Beilfuss, 2001].

3 SDDP model for the Zambezi basin

Stochastic dual dynamic programming model (SDDP) is an optimization technique well-suited to sequential decision-making problems. SDDP is an extension of the traditional discrete stochastic dynamic programming (SDP) that can handle a large state space, i.e. a large number of reservoirs. SDP solves the multistage decision-making problem by solving a set of recursive, one-stage, optimization problems in which the decision variables are chosen so as to maximize the sum
of expected immediate and future benefits. SDDP belongs to the so-called Approximate Dynamic Programming field where the main idea is to remove the computational burden associated with discrete DP consists of constructing an approximation of the benefit-to-go function. In SDDP, the approximation relies on piecewise linear functions which are constructed from the primal and dual information of the one-stage optimization problems. The reader should refer to Tilmant et al. [2008] for a detailed description of SDDP.

Assuming that the immediate benefit function \( f_t(.) \) is linear, and using \( L \) hyperplanes to approximate the benefit-to-go function \( F_{t+1} \), the one-stage SDDP optimization problem can be written as:

\[
F_t(s_t, q_{t-1}) = \max \{ f_t(s_t, q_t, r_t) + F_{t+1} \}
\]

subject to

\[
s_{t+1} - C_R(r_t + l_t) + i_t = s_t + q_t - e_t(s_t)
\]

where \( C_R \) is the connectivity matrix, \( s_t \) is a vector of storage volumes at the beginning of time \( t \), \( q_t \) is a vector of incremental flows, \( i_t \) is a vector of irrigation water withdrawals, \( r_t \) is a vector of turined outflows, \( l_t \) is a vector of spills, and \( e_t \) is a vector of evaporation losses, which are assumed to vary linearly with the known initial storage levels. This equation assumes that there is no lagging and attenuation of reservoirs releases because the monthly time step is large enough to ignore travel times between reservoirs. The next constraints specify lower and upper bounds on storages, releases and irrigation withdrawals:

\[
\underline{s}_{t+1} \leq s_{t+1} \leq \overline{s}_{t+1}
\]

\[
\underline{r}_t \leq r_t \leq \overline{r}_t
\]

\[
\underline{i}_t \leq i_t \leq \overline{i}_t
\]

while the following \( L \) constraints are the hyperplanes providing an outer approximation of \( F_{t+1} \)

\[
\begin{align*}
F_{t+1} - \varphi^{l^1}_{t+1} s_{t+1} & \leq \gamma^{l^1}_{t+1} q_t + \beta^{l^1}_{t+1} \\
\vdots \\
F_{t+1} - \varphi^{l^L}_{t+1} s_{t+1} & \leq \gamma^{l^L}_{t+1} q_t + \beta^{l^L}_{t+1}
\end{align*}
\]

where \( \varphi^{l^1}_{t+1}, \beta^{l^1}_{t+1} \) and \( \gamma^{l^1}_{t+1} \) are the parameters of the expected \( l^{th} \) hyperplane. The remaining constraints are the hyperplanes of the convex hulls representing the hydropower production functions

\[
\begin{align*}
\hat{P}_t - \psi^h s_{t+1}/2 - \omega^h r_t & \leq \delta^h + \psi^h s_t/2 \\
\vdots \\
\hat{P}_t - \psi^H s_{t+1}/2 - \omega^H r_t & \leq \delta^h + \psi^H s_t/2
\end{align*}
\]

where \( \hat{P}_t \) is the vector of approximated power generated during time period \( t \); \( \psi^h, \omega^h \) and \( \delta^h \) are the vectors of parameters.

The SDDP model for the Zambezi basin includes 17 nodes as depicted on Figure (1). Due to the low level of development in the upper Zambezi, a single node is used to represent irrigation and other consumptive uses in the upstream countries (Angola, Botswana, Namibia). 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 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
Figure 1: The Zambezi River Basin
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.

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 increase in energy
load will be matched by efficient gas-fired thermal power stations and by hydroelectric power
plants. Consequently, a value of 40 US$/MWh is attached to energy generated in the system. For
the irrigation demand sites, we assume horizontal demand curves where the at-site water value
is equal to 0.05 US$/m$^3$, which is consistent with international experience [Whittington et al.,
2005]. Crop water requirements are calculated for cereals and sugar cane with CROPWAT using
climatic data derived from CLIMWAT. Finally, horizontal demand curves are also attached to
the three largest wetlands considered in this study with an at-source water value of 0.01 US$/m$^3$ using
the same approach as in Tilmant et al. [2010].

4 Analysis of Simulation Results

Figure (2) shows the cumulative distribution function of the annual energy generation by each
power plant in the system. We can see that, under normal hydrological conditions, the Zambezi
system would generate around 60 TWh. During dry years, however, the production can be as low
as 40 TWh. The firm energy that can be guaranteed 90% of the time is around 48 TWh. As
expected from the installed capacity, the largest contribution comes from Cahora Bassa followed
by Mependa Uncua, both in Mozambique. They both account, on average, for more than half of
the energy generated in the basin.

If water were allocated to its most productive uses, the upstream irrigation areas would be in
a difficult position: the upstream farmers would face a coalition of downstream consumptive
and non-consumptive users and are therefore likely to see their entitlements curtailed, especially
during dry years when marginal water values increase throughout the basin. The comparison of
the maximum potential irrigated areas and the number of hectares that can be effectively irrigated
with the economically efficient allocation decisions is showed on Figure (3) and listed in Table 3.

The size of the vertical bars is proportional to the potential number of hectares that can be irri-
gated in the region. Each bar is then subdivided into two parts: in gray we have the proportion
of hectares that can effectively be irrigated, and in black we see the unserved irrigation areas.
Table 3: Potential and effectively irrigated areas

<table>
<thead>
<tr>
<th>Node</th>
<th>Potential area (ha)</th>
<th>Irrigated area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kafue Flats</td>
<td>40.000</td>
<td>30.680</td>
</tr>
<tr>
<td>Upper Kafue</td>
<td>20.000</td>
<td>660</td>
</tr>
<tr>
<td>Lower Kafue</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Upper Zambezi</td>
<td>17.930</td>
<td>310</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>141.230</td>
<td>5.850</td>
</tr>
<tr>
<td>Shire</td>
<td>169.520</td>
<td>169.520</td>
</tr>
<tr>
<td>Delta</td>
<td>91.960</td>
<td>91.960</td>
</tr>
<tr>
<td>Luangwa</td>
<td>167.460</td>
<td>23.950</td>
</tr>
</tbody>
</table>

We can see that most of the unserved irrigation areas are mainly located upstream. The comparison between the Kafue Flats and the Luangwa region reveals that the sugar cane plantations in the Kafue Flats manage to get water even though they are located upstream the most productive hydropower station (Kafue Gorge), whereas the cereals in the Luangwa region are not economically interesting. This illustrates the importance of the cropping pattern and the difference in agro-meteorological conditions throughout the basin.

Figure (4) displays the average monthly discharges in the three largest wetlands affected by dams and upstream water abstractions. The thin lines represent the historical, undisturbed, average monthly flows, whereas the thick lines indicate the average discharge after regulation and abstraction. We can see that the discharges in the delta remains fairly constant throughout the year despite the fact we value flood pulses during the high flow season (at-source water value = 0.01 US$/m^3$). The difference between the dry and wet season is more evident in the two wetlands upstream, the Mana Pools and the Kafue Flats. Restoring a flow regime in the delta will require that a larger value be attached to the environmental flows, which will further increase the opportunity costs in terms of energy and irrigation.

5 CONCLUSIONS AND RECOMMENDATIONS

As the competition for water is likely to increase in the near future due to socioeconomic development and population growth in the Zambezi, water resources managers will face hard choices when allocating water between competing users. When crop irrigation is involved, water is usually allocated by a system of annual rights to use a fixed, static volume of water, which is typically less than what farmers would expect. Such a static management approach may have significant opportunity costs when large agricultural areas are located in the upper reaches of the river basin. This study reveals that a massive development of irrigated agriculture based on cereals in the Upper Zambezi should be carefully weighted against the forgone energy and the disruption of major wetlands on which local communities rely. The sharing of the Zambezi waters should go hand in hand with the sharing of basin-wide benefits should upstream countries accept to forgo some of their benefits by reallocating water downstream.

ACKNOWLEDGMENTS

This work was part of the ADAPT project financed by CCES (Competence Center for Environment and Sustainability, ETH-Z, Switzerland) and by the POWER2FLOW project financed by the UNESCO-IHE Partnership Research Fund (The Netherlands)

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Figure 3: Irrigated Areas
Figure 4: Average Monthly Discharges in the Wetlands
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