

Evaluation of the Conflict Between Hydropower Generation and Flood Control in the Cahora Bassa Dam, Mozambique

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Abstract-Conflicts often arise for reservoirs with multiple water uses, such as hydropower generation, irrigation, and flood control. While high levels are desired to store water that will be used during the dry season for hydropower generation, low levels in the reservoirs may reduce flood damage. As most hydropower reservoirs are not designed for flood control, the operational planning usually seeks to minimize this conflict with careful allocation of appropriate space in the reservoirs for flood control. The present study compares the benefits provided by a reservoir for flood control versus those of a reservoir for hydropower generation, using a case study at the Zambezi River at the Cahora Bassa dam in Mozambique, Africa. The evaluation of these benefits was made using Monte Carlo simulations with synthetic series of natural inflows. The synthetic series were generated using inflow statistics from 1955 to 2012 at the Cahora Bassa dam. The results indicate that the consideration of flood control spaces in the reservoir results in a reduction of dependable energy, which in turn relies upon the return period considered and the proposed maximum outflow. Considering a return period of 100 years for flood control and 50 years for hydropower generation, an energy loss was observed of: 4 average MW for an outflow restriction of 15,000 m³.s⁻¹; 90 average MW for an outflow restriction of 10,000 m³.s⁻¹; and 196 average MW for an outflow restriction of 8,000 m³.s⁻¹. Therefore, as expected, there is an increase in energy loss for lower outflow restriction.

Keywords- Hydropower Generation; Flood Control; Synthetic Flow Series Generation

I. INTRODUCTION

This paper compares the benefits for a reservoir used for flood control versus the benefits of a reservoir used for hydropower generation. The benefit of flood control consists in a downstream peak flow reduction. For hydropower generation, the benefit is represented by the dependable energy provided by flow regularization. Hence, the outcome of the present study is a relation between peak flow reduction and dependable energy output, as provided by the reservoir operation. We evaluated both benefits on a probabilistic basis expressed by means of the respective return period.

When a hydropower reservoir is used simultaneously for flood control, conflicts arise. In order to guarantee future hydropower generation, it would be necessary to keep the reservoir at full levels for flood control while (paradoxically) keeping the reservoir at low levels in order to absorb future flood waves [1]. The operational experience in the Brazilian Hydro Plant System shows that in many instances hydropower reservoirs can also be used for flood control, as long as certain limitations are considered [2].

Flood control by reservoirs is based in allocating empty spaces in the reservoirs in order to absorb future floods. For hydropower reservoirs, however, if this space is large and there is no flood, future hydropower generation is at risk. The main purpose of these reservoirs is hydropower generation and flood control becomes evident.

When flows are seasonally defined, the effect of flood control on hydropower generation may be minimized by a seasonal allocation of flood control spaces. Furthermore, the determination of flood control volumes must consider not only hydrological aspects, but also the costs of energy shortage and the socioeconomic benefits provided by flood control [2].

A variety of methods to define flood control volumes in multiple-use reservoirs have been employed to minimize the conflict between different water uses. In Brazil, according to ONS (National System Operator, Portuguese abbreviation), the main use of large reservoirs is hydropower generation. Generally, flood control is a secondary purpose served by the reservoirs. Two methods are normally used to fulfill this secondary purpose: (1) the curve volume – time method [3], and (2) the critical trajectory method [4].

In the case of [5], the author presented a method that explores the integration between hydrological forecast and reservoir operation. This integrated system is able to predict the volumes to be allocated for flood control in real time.

In this paper, we propose a method based on flood frequency analysis combined with the Monte Carlo method for energy evaluation. Firstly, we did not use seasonality to allocate flood control volumes. We used an average head for energy evaluation. Secondly, we did consider flow seasonal variation, and we considered the head as a function of reservoir level fall. Our method is illustrated by a case study on the Zambezi River in Africa, specifically at the Cahora Bassa reservoir in Mozambique.

II. STUDY METHODS

The Zambezi is Mozambique's main river, the fourth largest in Africa, with a drainage area of 1,390,000 km² and a length of about 2,700 km. This river passes through eight countries [6]. The Cahora Bassa dam is situated in the Tete province and is the first large hydropower project built in Mozambique. The reservoir has a maximum storage of 65×10^9 m³ and a live storage of 52×10^9 m³ (equivalent to 602,000 m³. s⁻¹.day). The reservoir area is 2,900 km², with a length of 270 km, and 30 km of maximum width. The annual average evaporation is about $4,3 \times 10^9$ m³ (corresponding to 1,480 m.year⁻¹). Fig. 1 shows the location of the Cahora Bassa dam.

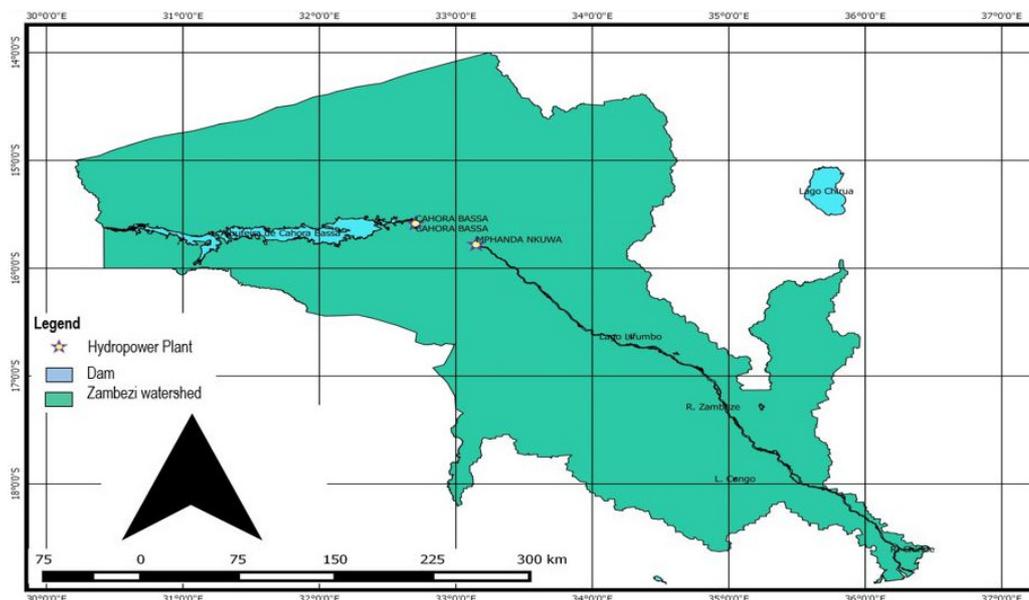


Fig. 1 Location of Cahora Bassa dam in Tete province, Mozambique

The Cahora Bassa dam has security systems composed of eight bottom outlets, with a total evacuation capacity of 12,800 m³.s⁻¹, as well as an automatic surface with maximum discharge capacity of 600 m³.s⁻¹. The dam has five-generation spillway groups catch one with a capacity of 455 m³.s⁻¹. The gross head is 103.5 m. The total maximum discharge capacity is therefore 15,665 m³.s⁻¹, when the five turbines are in operation [6].

A. Data

We used natural daily flows to analyze flood frequencies. For energy supply studies, synthetic average monthly flows were used. The synthetic flow series were generated based on statistical properties of historic flows in the E-320 hydrometric station, which belongs to the National Water Supervision (DNA, Portuguese abbreviation). This station is located in Tete province at 16°09'S and 33°35'E, at 118 m of altitude. The observation records span 58 years (1955-2012). For filling gaps in the historic series, linear regression (as discussed in [7]) and linear interpolation (described by [8]) were used. The synthetic flow series were generated by a disaggregation method we describe later on in this paper.

B. Annual Synthetic Series Generation

In our research, we used the Monte Carlo method to determine dependable energy. To do this, 1,000 synthetic series with a length of 50 years each were generated.

Simple monthly flow generation models are unable to preserve the observed annual flow autocorrelation and avoid the use of complex long memory models, so a disaggregation method was used. First, synthetic annual average flows were generated. Second, they were disaggregated into monthly average flows.

To generate the average annual flows, we employed LN3 distribution combined with a first order autoregressive model AR1. To generate normal random numbers, the algorithm proposed by [9] was used. Time-dependent standard normal variables series (Z_t), were generated by Equation(1) considering $Z_0 = 0$.

$$Z_t = \rho \times Z_{t-1} + (1 - \rho^2)^{1/2} \times Y_t \quad (1)$$

Here ρ is the autocorrelation coefficient of the normal transformed annual flows, and Y_t an independent standard normal variable. The standard normal variables are then transformed into a LN3 random variable, by Equation ().

$$X_t = \xi + \exp(Z_t \times \sigma_y + \mu_y) \tag{2}$$

Where X_t is the natural inflow at time t ; ξ is the lower inflow bound; $X_{(i)}$ is the ordered value of annual average flow; X_{median} is the median of annual average flow; μ_y and σ_y are the mean and standard deviation of $\ln(X - \xi)$; and n is the number of observations in the historical series. The parameters (σ_y , μ_y and ξ) are estimated by quartile method, using combined to maximum likelihood [10], using Equations (3), (4) and (5).

$$\hat{\mu}_y = \left[\sum_1^n \ln(X_i - \xi) \right] \times n^{-1} \tag{3}$$

$$\hat{\sigma}_y = \left[\sum_1^n \ln(X_i - \xi) - \mu_y \right]^2 \times n^{-1} \tag{4}$$

$$\xi = (X_i \times X_n - X_{\text{mediana}}^2) \times (X_1 + X_n - 2 \times X_{\text{mediana}})^{-1} \tag{5}$$

C. Annual to Monthly Series Disaggregation

After the generation of the synthetic annual flow series, we used the disaggregation model by hydrologic scenarios proposed by [11] in order to obtain monthly flows. This model performed well when compared to other classical disaggregation models, such as the Valencia and Schaake methods [4]. The model we employed showed equivalent results.

This method computes the ratio between each monthly flow and the average annual flow in each annual record, obtaining 58 vectors composed by 12 fragments each. We then selected randomly one of these vectors for each year of the synthetic series. Monthly flows were obtained by multiplying each fragment for an annual synthetic flow. A special procedure to guarantee the flows' consistency at the last and first month of successive years was used.

III. RESULTS

A. Flood Frequency Analysis

In [7], researchers performed a detailed analysis of flood frequency for the Zambezi River at the Cahora Bassa dam. They concluded that a Gumbel distribution is a better fit for maximum annual flows. Table 1 presents the results for maximum annual flows in several return periods.

TABLE 1 MAXIMUM ANNUAL FLOWS AT CAHORA BASSA DAM

Distribution	Method	Return Period Tr.C							
		2	5	10	20	50	100	1000	10000
Gumbel	MML	5800	9000	11000	13000	15600	17500	23900	30200
Exponential II	MML	5200	9000	11400	14100	17600	20260	29100	38000
GEV	MML	7600	11000	12800	14600	17000	18780	24400	30000
Log-Pearson III	MoM	5400	10300	11100	12400	15100	17900	26400	34300
Log-Normal	MoM	5500	8900	11400	14000	17700	20690	31400	38000

In the study featured in [7], they derived flood flow hydrographs using an average non-dimensional hydrograph for the ten largest historical floods, assuming 60 days of flood duration. The area between flood flow hydrograph and the horizontal line at the maximum outflow corresponds to the necessary flood control volume for the corresponding outflow restriction, given a specific return period. Table 2 shows these volumes.

TABLE 2 FLOOD CONTROL VOLUMES (M³) FOR SEVERAL RETURN PERIODS AND OUTFLOW RESTRICTIONS

Qr/Tr	2	5	10	20	50	100
8,000	0	0	1.92E+09	5.56E+09	1.36E+10	2.04E+10
9,000	0	0	6.57E+08	1.90E+09	8.98E+09	1.53E+10
10,000	0	0	1.73E+08	1.38E+09	5.58E+09	1.07E+10
11,000	0	0	0.01E+08	5.36E+08	3.35E+09	6.87E+09
12,000	0	0	0	1.53E+08	1.62E+09	4.51E+09
13,000	0	0	0	0	0.74E+09	2.55E+09
14,000	0	0	0	0	0.28E+09	1.27E+09

15,000	0	0	0	0	0.05E+09	0.61E+09
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For each time interval, we obtained the cumulative volume in the reservoir by calculating the difference between inflow and outflow, and then multiplying it by a time interval. Equation (6) shows this as follows:

$$\Delta V = (Q_A - Q_D) \times \Delta t \tag{6}$$

Here Q_A is the inflow; Q_D is the outflow; and Δt is the time interval. Therefore, the total accumulated volume during the flood period corresponds to the flood control volume, given by Equation (7).

$$V_e = \left[\sum_{t=0}^T (Q_A - Q_D) \right] \times \Delta t \tag{7}$$

The outflow Q_D is given by $(Q_D) = \min(Q_A, Q^*)$, with Q^* as the outflow restriction; V_e as the space volume; and Δt as the time interval considered (1 day = 86,400 seconds).

B. Power Supply Studies

1) Marginal Distribution:

The studies presented here were realized based on Monte Carlo simulations with synthetic average monthly flows. For the marginal distribution of mean annual flows, the lognormal distribution has been postulated. Statistical parameters were estimated from the historic records using the quartile/maximum likelihood method as described in the paper’s previous section (2.2). The estimated lower bound resulted essentially as $\xi = 0$; therefore, the LN3 distribution is reduced to an LN2 distribution. Hence, the marginal distribution adopted for mean annual flows was the lognormal LN2 distribution. Table 3 presents the statistical parameters in log-space.

TABLE 3 STATISTICS USED TO GENERATE SYNTHETIC FLOW SERIES

Method	Maximum likelihood
Average of log	7.51
Standard deviation of log	0.44
Skewness Coefficient of log	0.85
Autocorrelation of log	0.91

Fig. 2 indicates a good fit between the LN2 distribution and the observed flows.

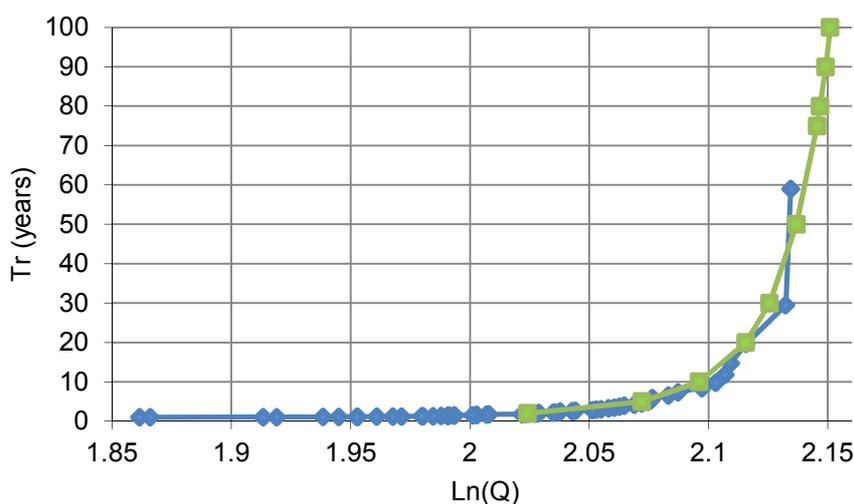


Fig. 2 LN2 adjustments

The blue line presents flow records, while the green line presents annual estimated flow

Applying the probability plot correlation test proposed by [12] to the LN2 model, we obtained a correlation coefficient ($\rho = 0.9957$). The critical value was 0.9764, since $n=50$ and $\alpha=0.05$ [10]. This indicates that the LN2 model is a good fit for the flow record.

2) Model Validation:

Our model validation was based on a comparison of the historical series with the synthetic series. We also used the cumulative frequency. The statistics of the synthetic series showed that is always an average among the 1,000 series generated. table 4 presents the statistical parameters such as average, standard deviation, slant, and autocorrelation coefficients, both for the synthetic and observed annual series.

TABLE 4 STATISTICAL PARAMETERS OF ANNUAL MEAN FLOW FOR SYNTHETIC AND OBSERVED SERIES
*AVERAGE VALUES AMONG THE 1,000 SYNTHETIC SERIES

Series average	Median	Standard Deviation	Slant	Autocorrelation
Historical	2,125	912	0.95	0.89
Synthetic*	2,005	823	0.52	0.98

Analyzing table 4, we can perceive a satisfactory representation of the synthetic series (for the observed series, analyzing the mean, standard deviation, and autocorrelation coefficient). Fig. 3 shows flow duration curves in log space for both historical and synthetic annual flows. In order to generate synthetic flows, we used a marginal LN3 distribution combined with an autoregressive first order AR1 model. Generally, the reproduced model has an effective performance in the annual flows generation.

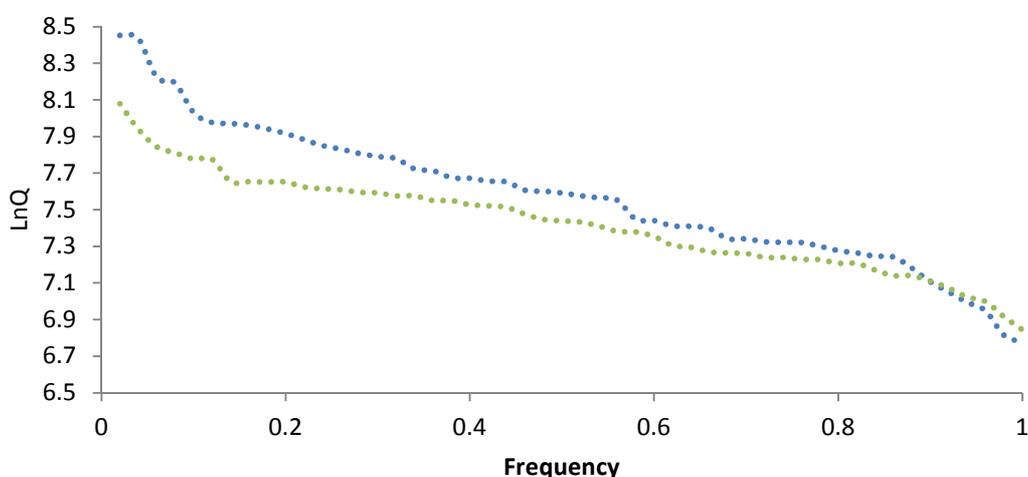


Fig. 3 Flow duration curves for observed and synthetic flows
Blue line = historical series, whereas green line = synthetic series

C. Dependable Energy Determination

The generated average monthly flows described in sections (2.2 and 2.3) are each transformed into natural energy of 50 years length series. According to [13], the natural energy of a hydro plant may be computed using Equation (8).

$$EN(t) = 0,0088 \times H_L \times Q(t) \quad (8)$$

Where EN(t) is the natural energy (average MW) at time t; H_L is the average net head (m); and Q(t) is the average discharge at time t ($m^3 \cdot s^{-1}$).

The coefficient 0.0088 corresponds to the product of water density ($1,000 \text{ kg} \cdot m^{-3}$), turbine (0.93) and generator efficiency (0.97), gravity acceleration ($9.81 \text{ m} \cdot s^{-2}$), and unit conversion (1,000,000). The Cahora Bassa dam has a gross head of 103.5m, which was reduced by 3% (allowing for head loss).

The volume available for regularization was assumed as the maximum storage of $52 \times 10^9 \text{ m}^3$. This was reduced by flood control volume (shown in table 2) for each maximum outflow and varying return periods. For each available volume, we performed a simulation using a thousand synthetic series X in order to obtain 1,000 values of regularized flows. These values were converted into firm energy applying Equation (). The simulations were performed for each synthetic flow series, as given by Equations (9), (10), (11) and (12).

$$V_{\max} = V - V^* \quad (9)$$

$$V(0) = V_{\max} \xrightarrow{\text{for}} t = 1, 2, 3, \dots, n \quad (10)$$

$$Q_t^* = \min(E \times K^{-1}, Q_{\max}) \quad (11)$$

$$V_t = \min(V_{\max}, V_{t-1} - Q_t^* + Q_t) \xrightarrow{\text{and vary until}} V_t \approx 0 \tag{12}$$

Here, V is the total net volume (19,800 m³.s⁻¹).month; V* is the flood control volume; Q_{max} is the maximum turbine flow; K is the plant productivity (K=0.0088H_L); Q_t is the natural inflow at time t; and Q_t* is the turbine outflow at time t.

We estimated the empirical cumulative distribution function through the relative frequency of ordered firm energies. We had to consider the medium fall liquid of energetic impacts resulting from space volume allocation for flood control, as well as utile volumes and maximum outflows. We observed a guaranteed energy loss and, in addition, an increase in the total operational cost.

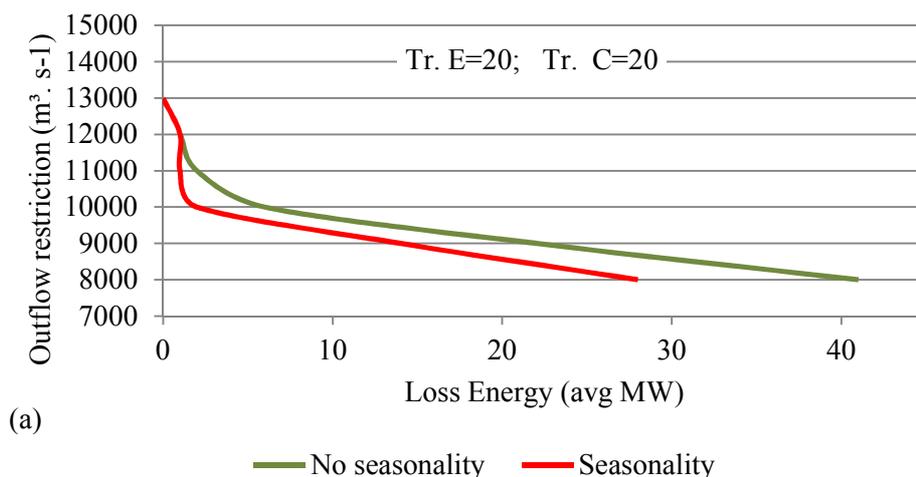
Using this cumulative distribution function, the dependable energy for any failure probability may be obtained through the calculation of volume. The return period may be computed by Equation (13).

$$T_R = [1 - (1 - r_n)^{1/n}]^{-1} \tag{13}$$

Here, r_n is the failure risk in n years (n=50, in this study). Considering a return period of 100 years for flood control and 50 years for hydropower generation in the Cahora Bassa reservoir, our study discovered an increasing trend in energy loss for lower outflow restrictions: 4MW for restriction flow of the 15,000 m³.s⁻¹, 90MW for 10,000 m³.s⁻¹, and 196MW for 8,000 m³.s⁻¹. If seasonality is also considered, the loss of dependable hydropower is reduced for the flood control volume's allocation.

When seasonality is taken into account for a return period of 100 years, during and after floods, we predict that a return period of 50 years would result in an energy loss of 2 average MW for restriction flow of the 15,000 m³.s⁻¹; 25 average MW for 10,000 m³.s⁻¹; and 44 average MW for restriction flow 8,000 m³.s⁻¹.

Since the dependable energy of the Cahora Bassa plant for these return periods is 1,519 average MW [14], the energy losses would be up to 12.9% without seasonality consideration and 3% with seasonality consideration. Fig. 4(a, b, c) show the dependable energy loss for various combinations of return periods for energy (Tr.E) and for floods (Tr.C).



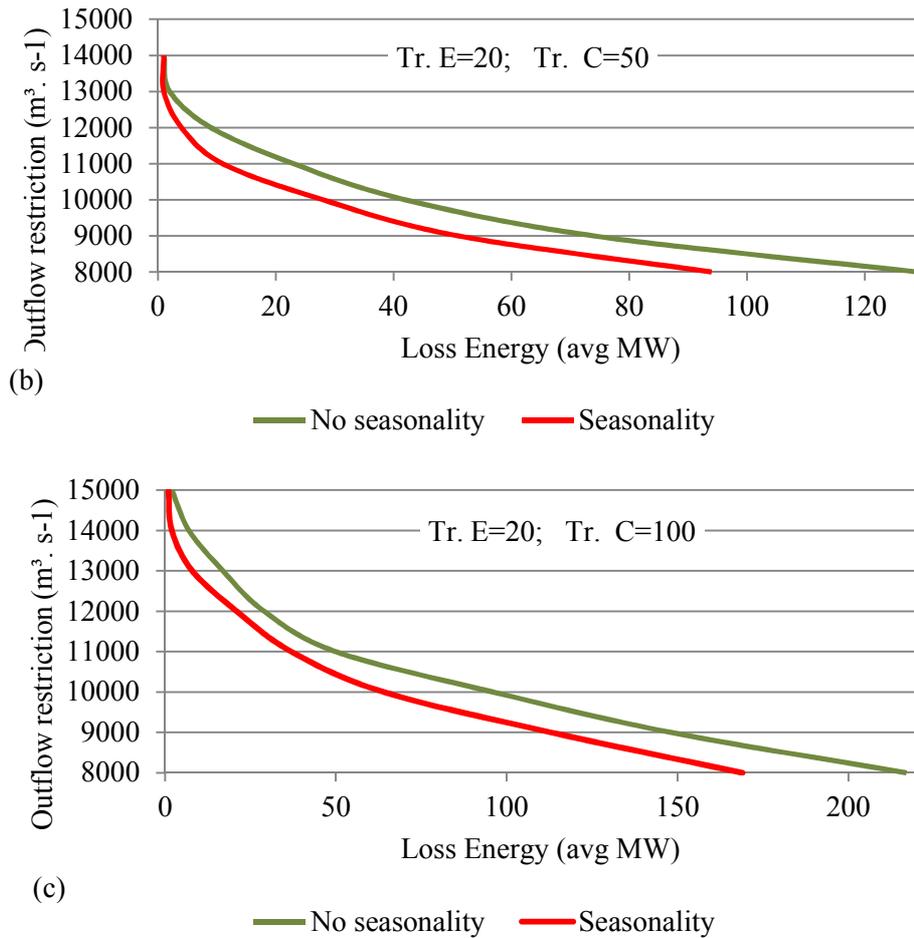
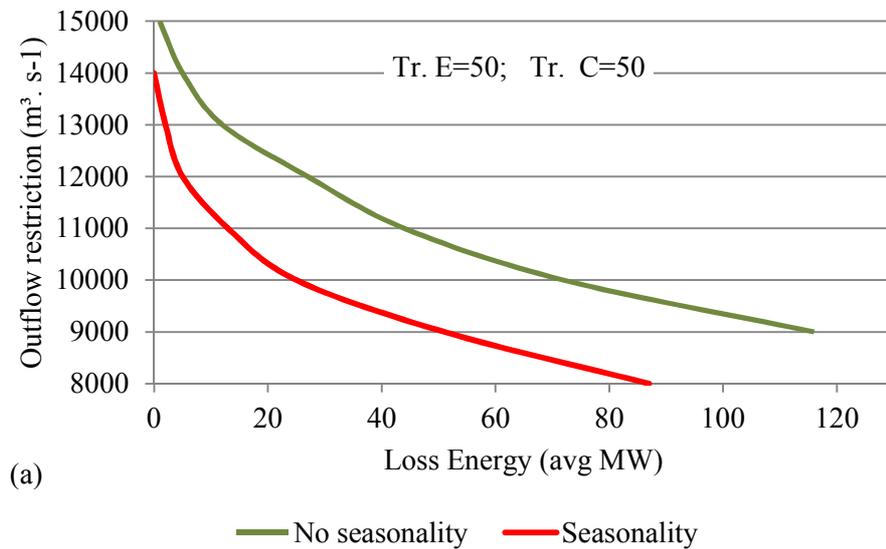


Fig. 4 (a, b, c) Energy loss for different return periods aiming at flood control and hydropower generation



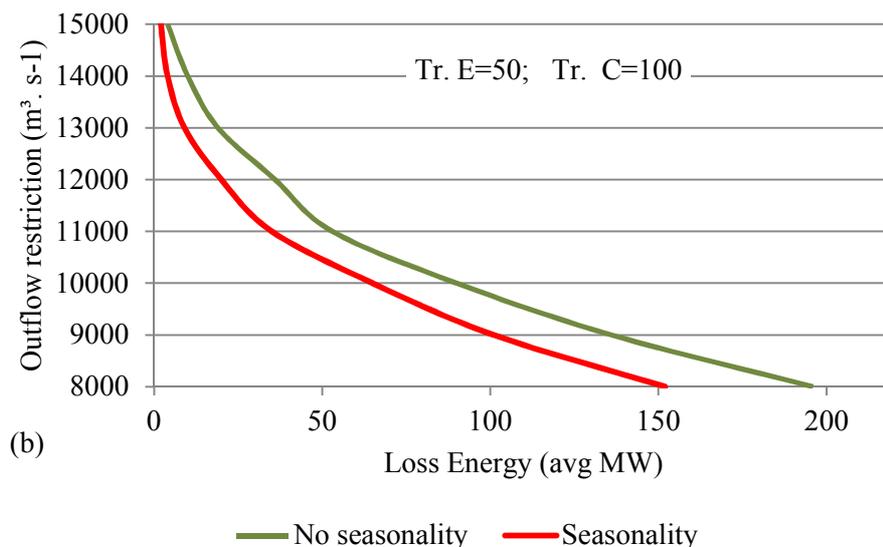


Fig. 5 (a, b) Energy loss for different return periods aiming at flood control and hydropower generation

Overall, considering seasonality and medium fall, the authors of this study make the recommendation of allocating the volumes only in the months with a positive probability of flows above outflow restriction ($P_r(Q_{max}) \neq 0$). As clearly seen in Fig. 5 (a, b), these results show a significant decrease of energy loss due to flood control.

Furthermore, the simulation may be refined using the variable head as a function of reservoir level for each month. In this case, the simulation procedure uses the plant productivity as a function of the reservoir volume. In the Equations (9), (10), (11), and (12) (simulation), we used $K = K(V_{t-1})$. In this case, energy losses are further reduced, as shown by Fig. 5 (taken from [14]).

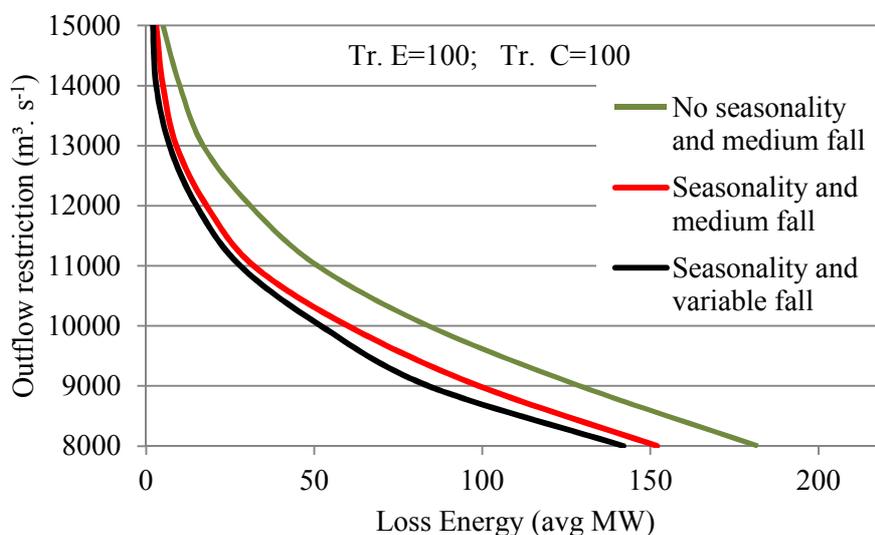


Fig. 5 Comparison of energy loss curves for a Tr.E=100 years and Tr.C=100 years for three different analysis

For a return period of 100 years for both energy and floods at $8,000 \text{ m}^3 \cdot \text{s}^{-1}$ outflow reduction, the loss is reduced from 152 average MW to 140 average MW.

IV. CONCLUSIONS

In this study, we estimated the energy loss relative to the case of no flood control (flood control volume 0) using Monte Carlo simulations with synthetic flow series. In various instances, these losses may be significant.

The simulation method we used on synthetic flow series generation at Cahora Bassa was suitable for synthetic series generation. Our study verified that LN2 is appropriate to model historical inflow series. Thus, it can be used to generate synthetic annual flow series. The evaluation of energetic impacts arose from flood control volumes allocation, allowing us to conclude that flood control reduces dependable energy. Therefore, it implies an increase in operational cost.

The results we obtained also led to the conclusion that considering spaces in the reservoir for flood control results in a reduction of dependable energy. This depends upon the return period considered, the restriction flow, and the seasonality of floods.

When we considered a return period of 100 years for flood control and 50 years for hydropower generation at the Cahora Bassa plant, we observed a trend of increasing energy loss, which reduced the maximum outflow restrictions. When seasonality is not considered, the results are 4 average MW for restriction flow of $15,000 \text{ m}^3 \cdot \text{s}^{-1}$; 90 average MW for $10,000 \text{ m}^3 \cdot \text{s}^{-1}$; and 196 average MW for a restriction flow $8,000 \text{ m}^3 \cdot \text{s}^{-1}$. Under the seasonality consideration, however, the results are 2 average MW, 25 average MW, and 44 average MW, respectively. Finally, when the variable head is considered, energy losses are around 8 to 12%.

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