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Generation of Synthetic Series for Long-Term Analysis of Optimal Operation Policies of a Cascade Hydroelectric Dam System

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Abstract: Stochastic Dynamic Programming (SDP) has been used to solve reservoir management problems in different parts of the world; specifically in Mexico, it has been used to obtain operating policies that optimize a given objective function. By simulating the operation of the system with a comprehensive model, the behavior of such policies can be accurately evaluated. An optimal policy involves, on the one hand, the selection of the volume of water to extract from each reservoir of the system that guarantees the maximum expected benefit from electricity generation in the long term; and, on the other hand, an optimal policy should reduce the occurrence of unwanted events such as spills, deficits, as well as volumes exceeding the guide curves imposed by the operators of the dams. In the case of the Grijalva river dam system, SDP was applied to determine optimal operating policies considering three alternative guide curves proposed by different agencies; however, since the simulation of the operation of the system under the three alternatives with the historical record of dam inflows found that none of them showed deficits or spills, it was considered necessary to use synthetic series of inflows to increase the stress of the system. Records of synthetic biweekly series of 1000 years were then generated to simulate the behavior of the Grijalva river dam system using the optimal operation policies obtained for each alternative. By stressing the dam system by simulating its behavior with synthetic series longer than the historical record but preserving the same statistical characteristics of the historical series on the synthetic ones, it was possible to realistically evaluate each operating policy considering the frequency and magnitude of spills and deficits that occurred at each dam. For the generation of the synthetic series, a fragment method was used; it was adapted to simultaneously generate the inflow volumes to the two regulating dams (modified Svanidze method), which preserves the statistical characteristics of the historical series, including both the autocorrelations of each series and the cross-correlation. It was also verified that simulating the operation of the dam system with the generated series also preserves the average conditions, such as the average biweekly generation at each dam, which were obtained in the simulations with the historical record. Finally, an optimal policy was obtained (Test 4) by combining the guide curves used in the previous tests. Such a policy attained an average energy production of 474 GWh/fortnight, the lowest average total spills in the system (30,261.93 hm^3), and limited deficits (5973.17 hm^3) in the long term. This represents a relative increase of 16% in energy generated compared to the balanced historical operation scenario with respect to the few events of spills and deficits.

Keywords: Grijalva dam system; modified Svanidze method; reservoir spills; reservoir deficits; hydroelectric dam

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1. Introduction

Stochastic Dynamic Programming (SDP) [1] has been used to solve reservoir management problems in different parts of the world [2–4]. Specifically in Mexico, it has been applied to obtain operation policies that optimize a given objective function [5–7]. The behavior of the system can be evaluated by simulating its operation.

The hydrological system of the Grijalva River has four large dams, two of which have large storage capacities. On such a system of dams, optimal operating policies were determined considering three alternative guide curves proposed by various agencies. However, the simulation of the system with the three alternatives and using the historical record did not produce deficits or spills, so it was considered necessary to use synthetic series of inflows to the reservoirs that stress the system the most.

In the field of Stochastic Hydrology, which aims to generate synthetic series that preserve the statistical behavior of different random variables over time [8–10], different procedures have been developed to generate synthetic records. Among them, the one developed by [11] proposed a model that seeks to preserve the mean, variance, and the autocorrelation coefficient of the series; in turn, Matalas and Young y Pisano [12,13] presented and developed an extension of Fiering's model. The Thomas–Fiering method has the advantage of preserving the first three statistical moments of the analyzed series; however, it is not guaranteed that these statistics can be preserved in the case of synthetically generating several time series with crossed autocorrelations.

Among the studies of the use of synthetic records to perform simulations in different engineering systems, the one by [14] determined the relationship between the size, reliability, and draught of a reservoir for a certain probability of failure. It also studied the effect of the parameters of the inflow probability distribution on the size of the reservoir. On the other hand, [15] described the distinctive periodic and non-Gaussian characteristics of typical river flow series and emphasized the hydrological importance of seasonality, marginal distribution, dependence, and crossover properties. The models discussed by these authors include short memory models, autoregressive models, Markov series, higher order autoregressive models, log-normal models, daily flow models, multi-site short memory models, long memory models, fast fractional Gaussian models, and broken line fractional noise models. Later, Mc Leod [16], studied the application of synthetic series to avoid bias in data sequences of stochastic processes using random initial values with the objective of avoiding bias. He also developed some simulation procedures with synthetic records obtained from Box Jenkins models; the author indicates that these synthetic generating methods can be used in the design of reservoirs.

Silva and Portela [17] proposed a procedure to generate synthetic series of annual and monthly flows that combines two models: a probabilistic one, applied at the annual timescale, and a monthly one, a deterministic disaggregation model. The disaggregation of annual flows into monthly flows uses the fragment method. A total of 1200 series were generated and evaluated; confidence intervals were established for the evaluation and the results show that, in general, the statistics of the samples are contained in these intervals.

Moreno and Salazar [10] used a Matalas model for the generation of multiple synthetic series with which hydrological processes involving several flows or several rivers can be modeled. The mean of the Matalas model (conditional mean) is the expected value of the independent linear regression models for each flow. For their part, Koivisto et al. [18] simulated time series to analyze the challenges in the face of variability and uncertainty of variable renewable energy use in existing grids and possible future grid expansion. Airton de Sousa and Belmino [19] applied to intermittent rivers in semi-arid areas of Brazil the SAGE software (Stochastische AbflussGEnerierungsmodell), which obtains synthetic time series using 10 different procedures, highlighting that the Frag 1 and Frag 2 fragment methods, as well as the Fiering PAR model modified by Matalas, reported the lowest mean square errors and managed to better reproduce the historical behavior of the monthly flow rates of the intermittent rivers analyzed. The authors of [20] combined Fourier transform phase randomization simulation (based on time-domain series) with a flexible four-parameter kappa distribution, which allowed extrapolation to low and high levels not yet observed.

Talbot et al. [21] implemented Fourier VARMA in the RAVEN risk analysis and uncertainty quantification software framework, along with examples of correlated synthetic history generation. Mehr et al. [22] obtained a genetic programming (GP) model dataset for streamflow forecasting in a lake–river system for a watershed in Finland, to which they decided to add new data from the time series-based model (SARIMA) to improve the predictive accuracy of models for monthly streamflow forecasts. The independent GP and SARIMA models showed good accuracy in daily and weekly flow forecasting; however, for long-term modeling, the hybrid PG-SARIMA model showed better results but underestimated peak flows. Herein, for the generation of periodic series with cross autocorrelation, it is considered that the proposed modified Svanidze method is the ideal one, since the historical distribution function of both the total annual volume and the fortnightly behavior are preserved. With a technique using AI combined with the ARIMA model, it must be validated that these properties of the series are satisfied.

Lin et al. [23] proposed a time series analysis for an adaptive design framework under nonstationary conditions, developing a dynamic Bayesian autoregressive moving average (t-ARMA) model to simulate a standardized runoff index (SRI) time series; the results were compared with those of the traditional ARMA model.

Many of the synthetic record generation methods cited here are based on considering that the distribution functions of the time series can be represented with Normal type functions; still, in the study of [7], the simulation of optimal operation policies considering continuous functions and synthetic series obtained with Normal type distribution functions for the Grijalva river dams was completed. However, in a recent update of the data, it was found that the behavior of the annual inflow volumes to the reservoirs of greater regulation capacity obey a Gumbel type distribution. Thus, in this case, we used a generation method based on fragments, such as the Modified Svanidze [24,25], which considers the self-correlations and cross-correlations between the inflow volumes to each reservoir and can take into account a behavior of the historical annual inflows characterized by a distribution function different from the Normal, in order to subsequently disaggregate the annual values to a monthly, fortnightly, or even weekly scale.

In the next sections, a summary of the Stochastic Dynamic Programming method applied to optimize the operation policies of a dam system is presented first, followed by a description of the proposed synthetic record generation method and the case study data. Subsequently, we first present a summary of the results obtained by simulating the behavior of the policies associated with three alternatives of proposed guide curves, followed by an evaluation of the proposed synthetic record generation method with respect to its capacity to reproduce the statistics of the historical series. Once the relevance of the proposed synthetic record generation method has been validated, the results of the simulation of the behavior of the system are presented using 10 series of records generated, each for 1000 years, for the three alternative operating policies. From the analysis of the results obtained, a fourth alternative of guide curves was derived; with it, the behavior of the dam system can be improved. Finally, the conclusions derived from the research are highlighted.

2. Case Study

The Grijalva River is approximately 700 km long and is the second largest river in Mexico; it belongs to hydrographic region No. 30, Grijalva Usumacinta, located in southern Mexico; the basin includes the Upper, Middle, and Lower Grijalva; it originates in Guatemala. The Middle and Upper Grijalva cover the central area of Chiapas and the lower Grijalva is located in the plains of Villahermosa, Tabasco.

The Grijalva River continues its course to the Gulf of Mexico, passing through the lowlands of Tabasco, Mexico, which has caused recurrent flooding and significant damage in the area, as in the case of 2020, due to cold fronts 4 and 5 together with tropical storm Gamma, whose effects were reflected between 25 September and 6 October, and later, between 29 October and 2 November, cold fronts 9 and 11 also caused serious problems to the population downstream of the Peñitas Dam.

In the middle reaches of the Grijalva River, a hydroelectric system of four cascading dams was built: La Angostura (Belisario Domínguez), Chicoasén (Manuel Moreno Torres), Malpaso (Netzahualcóyotl), and Peñitas (Ángel Albino Corzo) [26,27] (Figure 1), which, in addition to generating electricity, help to manage floods to protect the Tabasco floodplain.

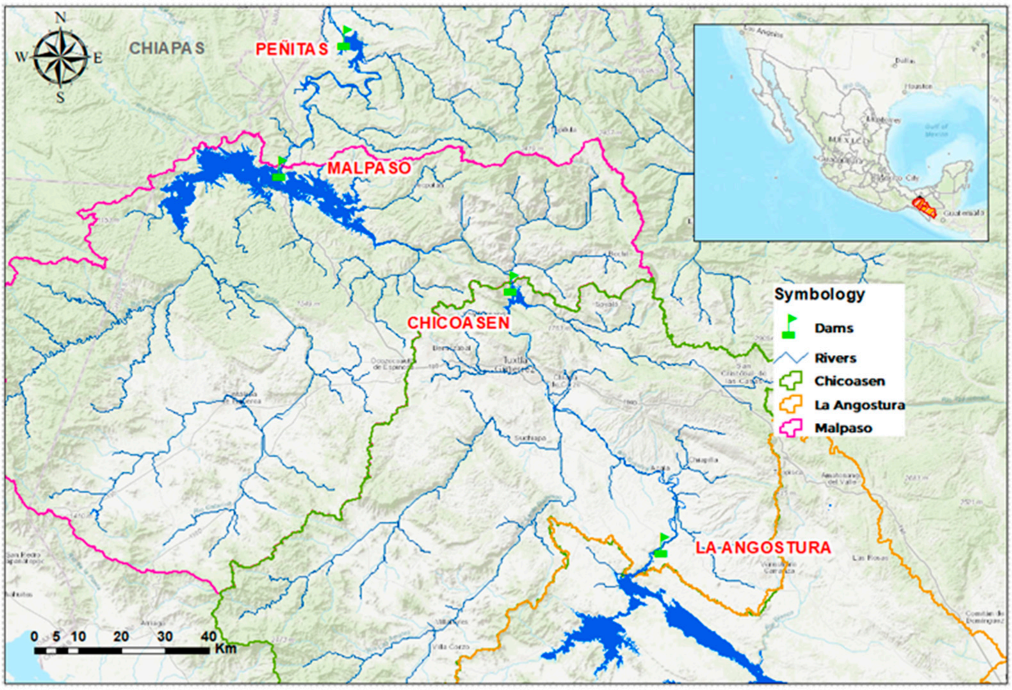

Figure 1. Location of dams in the Grijalva System. Source: Adapted with permission from [28].

La Angostura and Malpaso are the dams with the largest regulation capacity; they have a useful capacity of 13,169 and 9317 hm^3 compared to Chicoasén and Peñitas, whose useful capacities are 251 and 130 hm^3, respectively. Therefore, it is possible to work with an equivalent system formed by two dams (La Angostura and Malpaso), considering the head of the Chicoasén and Peñitas dams, whose operation basically consists of extracting what is discharged by La Angostura and Malpaso, respectively, trying to maintain prefixed levels, depending on the time of the year.

The dams of the Grijalva system are managed by the Federal Electricity Commission (CFE), which takes into account the guidelines of the National Water Commission (CONAGUA). Its operation policy has been updated based on technical studies conducted by the Engineering Institute (II) of the National Autonomous University of Mexico (UNAM) and the works [29–31], in which an objective function that considers power generation and undesirable situations of spills and deficits is used. It also adds guide curves [32], which work as a preventive traffic light to avoid those undesirable events.

Given the problems caused by the floods that occurred in 2020 in the Tabasco floodplain, three proposals were made to modify the current guide curves. One was proposed by the Federal Electricity Commission, CFE, another by the National Water Commission, CONAGUA, and another by the Engineering Institute of the UNAM. To objectively evaluate these proposals, the optimal operation policies associated with each of them were obtained and their operation was simulated, assuming that the historically recorded inflows will be presented [33,34]; however, in none of the three cases did spill or deficit events occur, which makes it difficult to compare their effectiveness.

Therefore, the objective of this research is to generate synthetic records that allow the long-term operation evaluation of the system of dams, under more unfavorable conditions, for the operation policies associated with the three proposed guide curves.

3. Methodology

3.1. Stochastic Dynamic Programming (SDP) Applied to a Cascade Reservoir System

Stochastic dynamic programming (SDP) [1] considers the randomness of reservoir inflow volumes. It is necessary to define an objective function that obtains, on the one hand, the maximum benefits per generation and, on the other hand, the reduction of undesired events. The restrictions of the problem are also defined, and the final goal is to obtain, for each state of the system and each stage of the year, the extractions, k*, corresponding to the optimum benefit for each dam of the system; these extractions are finally expressed as volumes of water to be extracted from each reservoir, depending on the level at which they are located and the time of the year.

To consider that the inflows are random, since its occurrence cannot be predicted with certainty, their probability density function is taken into account, from which the transition probabilities are obtained, i.e., that a dam will pass from a filling state i to a filling state j, given a certain extraction k.

The following steps are recommended for the application of dynamic programming [26]:

1. Define sequential decision steps (time intervals Δt);
2. Separate the problem variables into state variables (storage at each dam) and control variables (decision variables);
3. Define an equation of the state of the system that relates the state variables to the decision variables;
4. Establish an objective function that can independently evaluate the contribution of each stage to the final objective;
5. Impose constraints that are independent of the behavior of the system in other phases.

The sequential decision stages were defined by dividing the year into groups of consecutive fortnights according to fortnights that have similar historical averages of inflow volumes. The state variables are the storage levels of the reservoirs, which depend on the inflows to each reservoir (random variable) and the proposed withdrawals (decision variables).

The continuity equation governing the operation of a dam, considering a time interval Δt, is expressed as [35]:

$$\boldsymbol{S_j} = \boldsymbol{S_i} + \boldsymbol{VI_J} - \boldsymbol{VS_J}, \tag{1}$$

where

$\boldsymbol{S_i}$ and $\boldsymbol{S_j}$ are volume of storages at the beginning and end of the interval Δt, respectively. $\boldsymbol{VI_J}$ is the volume of inflow during the interval Δt, and $\boldsymbol{VS_J}$ is volume withdrawn during the interval Δt.

The inflow to the reservoir in the interval Δt is the random variable, characterized by a probability distribution function that depends on the time of year to which the time interval belongs; it is the stochastic and uncontrollable variable.

The system is subject to the following restrictions:

$$\boldsymbol{VS_{min}} \leq \boldsymbol{VS} \leq \boldsymbol{VS_{max}}, \tag{2}$$

$$\boldsymbol{S_{min}} \leq \boldsymbol{S_j} \leq \boldsymbol{S_{max}} \tag{3}$$

By dividing the useful volume of the reservoir into NS intervals (number of states) of magnitude ΔV, using the same interval to discretize all variables, the continuity equation takes the form:

$$j = i + x - k \tag{4}$$

Subject to restrictions:

$$kmin \leq k \leq kmax, \tag{5}$$

$$1 \leq j \leq NS, \tag{6}$$

where

i and j are the storage at beginning and end of stage,

x are the inflows to the reservoir during the stage (constitutes the random variable),

k is the volume withdrawal to the reservoir during the stage (this is the decision variable), and

$kmin$ and $kmax$, are the minimum and maximum extractions during the stage.

The benefit corresponding to any stage n depends on the volume extracted k, and the storage i and j at the beginning and at the end of the stage, so that the profit can be expressed as $b_n^k(i, j)$.

The aim is to find an extraction policy for two dams $k_l^n(i_1, i_2)$ that indicates the extraction to be made for reservoir l during stage n in terms of initial states (i_1, i_2) to maximize the cumulative benefit over the n stages of operation of the dams.

In the case of the Grijalva System dams, the proposed objective function seeks to maximize the expected value of the benefits of electric power generation, imposing penalties in the case of undesired events of deficit (in water demands for generation or drinking water supply), spillage, or overflow of the guide curves, as shown here:

$$\mathrm{OF} = \mathrm{Max}\ \mathrm{E}\left\{\sum_{l=1}^{NP} GE_l - C_l Der_l - C_l Def_l - C_l V_{cga_l} - C_l V_{cgb_l}\right\}, \tag{7}$$

where E() is the operator expected value; NP is the number of reservoirs (two, in this study); GE is the generated energy; Der, Def, V_{cga}, and V_{cgb} are spill, deficit, volume above the high guide curve (UCG), and volume below the high guide curve (LGC), respectively; and C_l are penalty coefficients for spill, deficit, or exceeding the UCG and falling below the LGC, respectively.

To obtain the maximum expected benefit, in a planning horizon of N years, it is assumed that the benefits are zero at the end of the analysis and the goal is to guarantee convergence to an optimal extraction policy for each stage n into which the year and each state i is divided.

The stochastic dynamic programming algorithm is solved with a backward process, i.e., a certain number of years N are defined, after which the benefits are considered zero, and the calculation is performed from that year N to year 1.

Considering the random nature of inflows and the fact that operating policies will be defined for a system consisting of two reservoirs whose operation is in series, the withdrawal policy should lead to obtaining the maximum expected benefit; the recursive equation results are [34]:

$$B_n^{k_1,k_2}(i_1, i_2) = \sum_{j_1=1}^{NS_J} \sum_{j_2=1}^{NS_J} q_{n,\,k_1}(i_1, j_1) q_{n,\,k}(i_2, j_2) \left[\left\{b_{n,\,k}(i_1, j_1) + b_{n,k_1,k_2}(i_1, j_1, i_2, j_2)\right\} + B_{n+1}^*\ (j_1, j_2)\right] \tag{8}$$

where:

$$\mathrm{B}_{\mathrm{n+1}}^*\ (\mathrm{j_1, j_2}) = \max_{\mathrm{k_1,k_2}}\left\{\mathrm{B_n^{k_1,k_2}}(\mathrm{i_1, i_2})\right\}$$

where $q_{n,k_l}(i_l, j_l)$ is the probability, at each dam, of passing from state i to state j, during stage n, given extraction k.

According to the continuity equation, $j = i + x - k$, the transition probability $q_{n,k_l}(i_l, j_l)$ depends only on-stage n and income, $x_l = j_l - i_l + k_l$ that is:

$$q_{n,k_l}(i_l, j_l) = \mathrm{f_n}(\mathrm{x_l})$$

3.2. Guide Curves

The guide curves are maximum elevations and storage suggested by the operating agencies that can reach the main dams of a country. Their purpose is to avoid undesired events (mainly spills) [27,30,36]. They are represented as elevation–time or volume–time graphs.

3.3. Generation of Synthetic Series

3.3.1. Svanidze's Fragment Method

Svanidze proposed a method in 1961; in essence, it is based on double random sampling. The first is the total annual inflow, similar to Grinevich [37], and the second is the fragments $q(t)$ corresponding to the stages into which the year is divided. By multiplying the total annual inflow Q by the fragments (monthly, biweekly, or weekly), we obtain a new hydrograph formed from monthly, biweekly, or weekly intervals. The combination of randomly generated total annual inflows multiplied by the fragments of a randomly selected year allows the generation of a hydrological series of as many years as required.

3.3.2. Modified Svamidze Method

To obtain synthetic series of two fortnightly records of the volumes entering reservoirs, as is the case of the analyzed system, the Svanidze fragment method is modified. First, the sum of the total annual volumes of the two records (in this case, of La Angostura and Malpaso) is calculated, determining the volume percentage that corresponds to each dam of that sum [38].

Additionally, the fractions of the volumes are determined for each fortnight of the year [39]. To randomly generate synthetic values of the total volume, the probability distribution function to which the historical total volume best fits is considered (obtained with a method of frequency analysis and, in this case, the method of moments to obtain its parameters). Random selection with replacement was utilized, using uniformly distributed numbers to select from historical data with a linear relationship. If the selected year changes, the behavior of the fortnightly data obtained synthetically does change, but its value also depends on the total volume, which is also randomly generated, but according to its probability distribution function.

To generate the fortnightly volumes corresponding to each series, a year is randomly selected; for the selected year, the total volume generated is multiplied by the percentage corresponding to each series, thus determining the total annual volume of each one. With this volume and the fractions of each fortnight of the randomly selected year, the volumes corresponding to each fortnight are obtained.

On the other hand, to minimize the problem of low correlation between the last month of one year and the first month of the following year obtained when applying the method, we worked with hydrological years that begin in the second half of October of year i and end in the first half of October of year $i + 1$, because in this way we move from the wet season to the dry season, and therefore the correlation is naturally low. Since the lowest correlation of inflow volumes occurs from the selected fortnight of October to the following fortnight, a hydrological year was used with such a beginning and end.

3.4. Data Set Used for the SDP

For the use of SDP in this analysis, the year was divided into seven stages, ensuring that their statistics (mainly the mean) were similar. With such approximation, the dimensions of the problem are reduced. The volume increment (ΔV) to discretize the state variables was set at 200 hm^3, discretizing the useful capacity into 65 states for La Angostura and 46 for Malpaso (previous studies of the system considered a volume increment (ΔV = 600 hm^3, so this analysis has a finer resolution). The maximum ($kmax$) and minimum ($kmin$) extractions were defined according to the extraction capacities of the dams and the drinking water supply requirements of the cities of Tuxtla Gutierrez, Chis. and Villahermosa, Tab. The capacities of the turbines of La Angostura (1100 m^3/s) and Malpaso (1400 m^3/s), which are equivalent to 1412.5 hm^3 and 1866 hm^{3,} respectively, per fortnight, were taken as input data, and a flow of 200 m^3/s was defined for drinking water supply in La Angostura and

300 m^3/s for Malpaso. The values of kmin and kmax considered in each of the seven stages are shown in Table 1.

Table 1. Optimization conditions for *kmin* and *kmax*.

ΔV	200 hm^3	La Angostura		Malpaso	
Stages	**Fortnights**	***kmin***	***kmax***	***kmin***	***kmax***
1	November–December	6	29	8	38
	October	3	15	4	19
	September	3	15	4	19
	August	3	15	4	19
5	July	3	15	4	19
	Q2 May–June	4	22	6	28
	January–Q1 May	12	64	16	84

3.4.1. Penalty Coefficients

Penalty coefficients do not have a monetary significance. Their intention is to decrease the value of the expected benefit per generation each time an undesired event of deficit, spillage, or volumes exceeding guide curves occurs. The increase or decrease in the coefficients is evaluated with the results of the simulation of different optimal policies. The penalty coefficients considered are shown in Table 2.

Table 2. Conditions for optimization: penalty coefficients for spill, deficit, and overrun of high (cga) and low (cgb) guide curves.

Stages		La Angostura				Malpaso			
		Spill	**Deficit**	**Surpasses cga**	**Below cgb**	**Spill**	**Deficit**	**Surpasses cga**	**Below cgb**
1	November–December	10	10	50	50	100	10	100	50
	October	10	10	80	50	100	10	100	50
	September	10	10	200	50	100	10	150	50
	August	10	10	200	50	100	10	150	50
5	July	10	10	150	50	100	10	100	50
	Q2 May–June	10	10	90	50	100	10	90	50
	January–Q1 May	10	10	50	50	100	10	80	50

3.4.2. Tried and Tested Policies

Three alternatives of proposed guide curves were considered. The results obtained with each of them will be referred to as Test 1, Test 2, and Test 3.

The same low guide curves are used in all three tests.

Figure 2 shows the high guide curves corresponding to each test for the La Angostura and Malpaso dams, respectively. The maximum operating water level (MOWL) is also drawn in said figure.

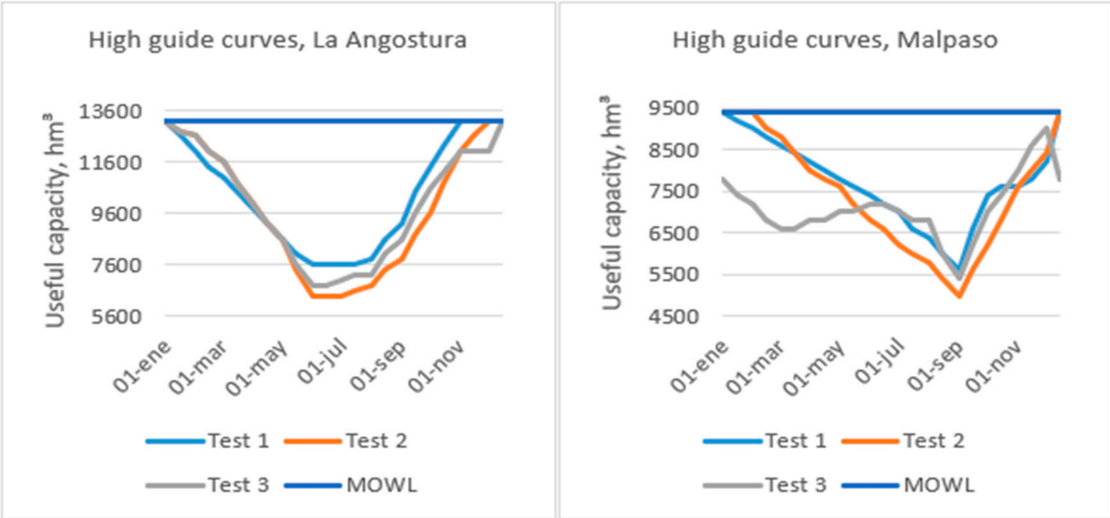

Figure 2. Guide curves tested for La Angostura and Malpaso.

4. Application and Results

4.1. Simulation of System Behavior with the Historical Record

Tables 3 and 4 show a summary of the results obtained with the simulation of the historical record, with the three proposed high guide curves.

Table 3. Results of policies tested: energy, deficit, and spillover.

Policy	Average Energy/Fortnight [GWh]			Deficit [hm^3]		Spill [hm^3]	
	La Angostura	Malpaso	Total	La Angostura	Malpaso	La Angostura	Malpaso
Test 1	280	201.29	481.29	0	0	0	0
Test 2	279.19	195.75	474.94	0	0	0	0
Test 3	279.45	197.18	476.63	0	0	0	0

Table 4. Results of the tested policies: minimum and maximum initial storage.

Policy	Minimum Initial Storage [hm^3]			Max. Initial Storage [hm^3]		
	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total
Test 1	1920	2035	3955	10,473	8355	18,828
Test 2	1577	1278	2855	9361	7881	17,242
Test 3	1842	1582	3424	9698	8084	17,782

With the 62 years of historical record, spill events or deficits did not occur on any occasion, making the analysis difficult to select the best-proposed high guide curve. Therefore, a long-term analysis of the three proposed guide curves is needed. With such a perspective, it was considered necessary to use synthetic series generated with the modified Svanidze method to analyze the behavior of the dam system under more critical conditions. The characteristics of the synthetic series generated in comparison with the historical series of inflow to the two reservoirs are described below.

4.2. Comparative Analysis of the Statistics of the Generated Series vs. the Historical Series

Figure 3 shows the comparison between the empirical distribution function of the sum of the total annual inflow volumes to the two dams obtained for the measured data and those corresponding to the data generated for the 10 synthetic series generated by the modified Svanidze method.

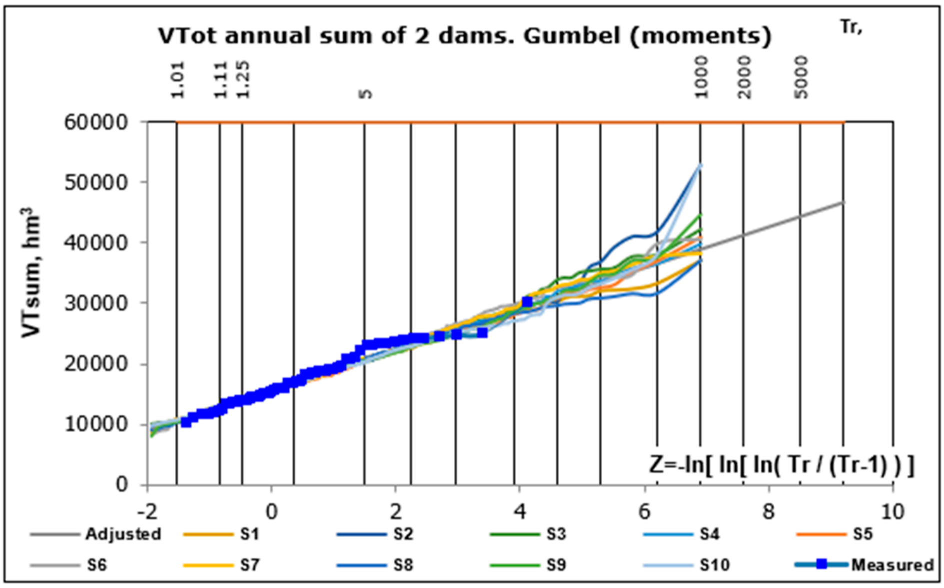

Figure 3. Probability distribution functions for the historical series and the 10 synthetic series generated with the modified Svanidze method.

To visualize the ability of the record generation method in preserving the statistics of the historical series, Figures 4–8 were made to show the mean, standard deviation, skewness coefficient, autocorrelation coefficient, and cross autocorrelation coefficient.

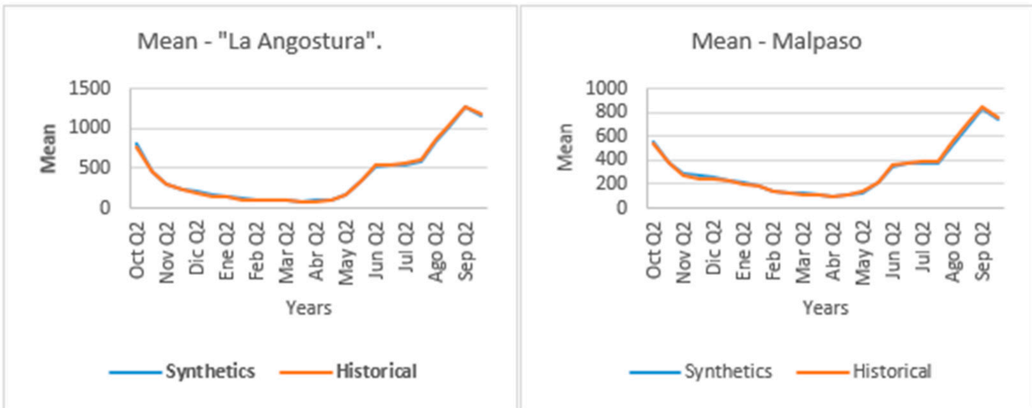

Figure 4. Comparison of the mean, average of the 10 synthetic series vs. historical series of La Angostura and Malpaso Dams.

The synthetic series generated accomplish the objective of creating more stressful scenarios than the historical ones, both in terms of drier periods and periods of larger runoff, as shown in Figure 3, but at the same time they adequately preserve the fundamental statistical characteristics of the historical record, as shown in Figures 4–8.

4.3. Simulation of the System Behavior with the Synthetic Registers for the Three Alternative Operating Policies

Tables 5–7 show the results of the energy generated per fortnight, as well as the spills and deficits obtained with the long-term simulation, based on the generation of 10 synthetic series.

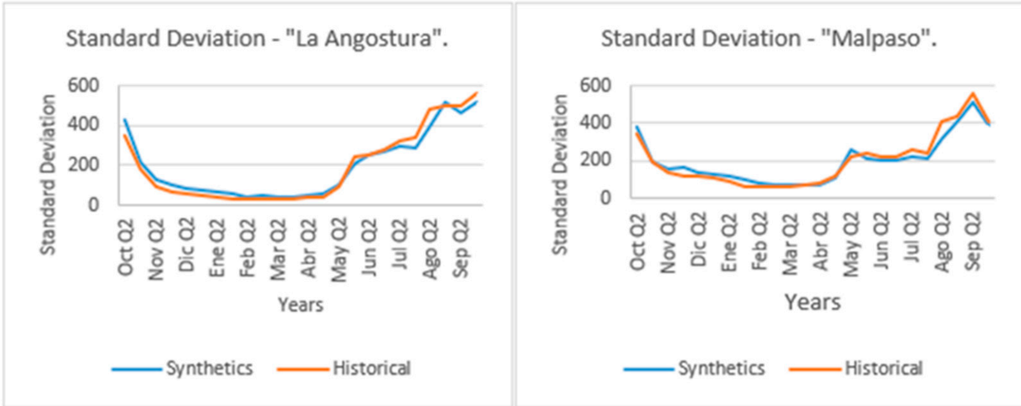

Figure 5. Comparison of standard deviation and average of the 10 synthetic series vs. historical series of La Angostura and Malpaso Dams.

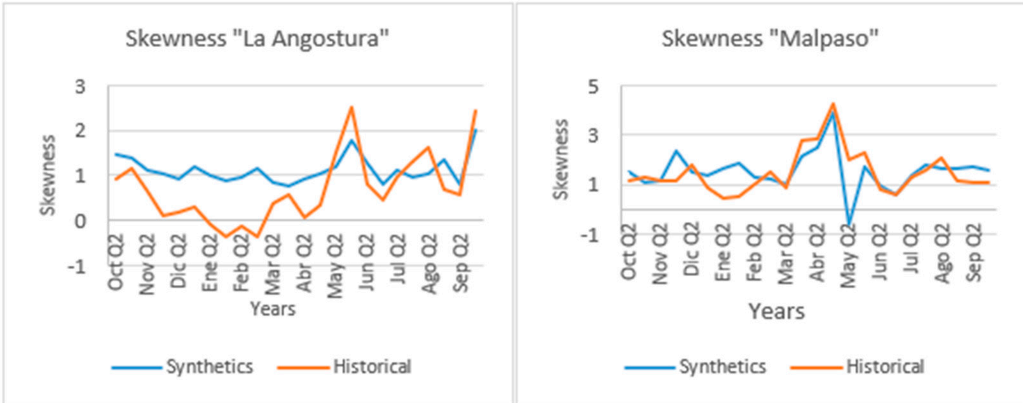

Figure 6. Comparison of the skewness coefficient and average of the 10 synthetic series vs. historical series of La Angostura and Malpaso Dams.

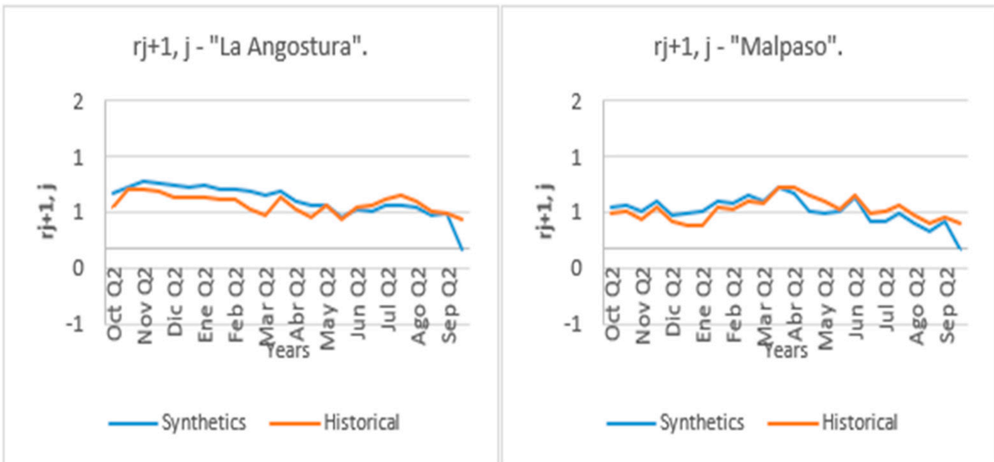

Figure 7. Comparison of the autocorrelation coefficient and average of the 10 synthetic series vs. historical series of La Angostura and Malpaso Dams.

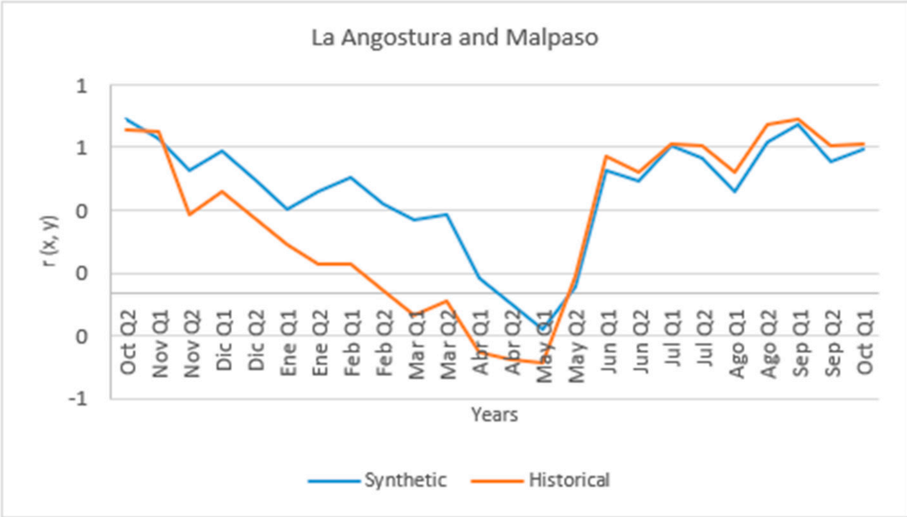

Figure 8. Comparison of the cross-correlation coefficient (rxy) of the 10 synthetic series of La Angostura and Malpaso dams.

Table 5. Summary of the joint simulation of La Angostura and Malpaso dams. Energy generated per fortnight.

Simulation	Test 1			Test 2			Test 3		
	Energy Generated [GWh/Fortnight].			Energy Generated [GWh/Fortnight].			Energy Generated [GWh/Fortnight].		
	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total
SS 1	277.3	199.0	476.3	276.4	193.1	469.5	276.9	194.6	471.6
SS 2	278.5	200.2	478.7	277.6	194.4	472.0	278.2	195.9	474.1
SS 3	275.9	198.8	474.7	275.0	193.0	467.9	275.5	194.5	470.0
SS 4	280.6	199.8	480.4	279.7	194.0	473.7	280.2	195.5	475.7
SS 5	275.1	196.8	471.9	274.2	191.0	465.3	274.7	192.6	467.3
SS 6	283.0	202.0	485.1	282.0	196.1	478.2	282.6	197.7	480.2
SS 7	279.6	200.4	480.1	278.7	194.6	473.3	279.2	196.1	475.3
SS 8	279.3	201.1	480.4	278.3	195.2	473.6	278.9	196.7	475.6
SS 9	276.6	198.1	474.7	275.7	192.3	468.0	276.3	193.8	470.0
SS 10	278.5	198.7	477.2	277.6	192.9	470.5	278.1	194.4	472.5
Average	278.5	199.5	477.9	277.5	193.7	471.2	278.1	195.2	473.2

Table 6. Summary of the joint simulation of La Angostura and Malpaso dams: **spill**.

Simulation	Test 1			Test 2			Test 3		
	Spill [hm^3]			Spill [hm^3]			Spill [hm^3]		
	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total
SS 1	0	588.81	588.81	0.00	0.00	0.00	0	281.68	281.68
SS 2	2493.03	14,124.63	16,617.66	857.23	7515.74	8372.97	1241.41	9669.79	10,911.2
SS 3	0	8956.77	8956.77	0.00	4573.96	4573.96	0	6693.89	6693.89
SS 4	0	5517.34	5517.34	0.00	2843.52	2843.52	0	4140.30	4140.3
SS 5	559.29	2341.17	2900.46	0.00	1292.29	1292.29	0	1431.35	1431.35
SS 6	0	2715.2	2715.20	0.00	1828.20	1828.20	0	2203.22	2203.22

Table 6. *Cont.*

Simulation	**Test 1**			**Test 2**			**Test 3**		
	Spill [hm^3]			**Spill [hm^3]**			**Spill [hm^3]**		
	La Angostura	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**
SS 7	0	2972.39	2972.39	0.00	1512.09	1512.09	0	1960.34	1960.34
SS 8	0	0	0.00	0.00	0.00	0.00	0	0	0
SS 9	0	4017.13	4017.13	0.00	2063.35	2063.35	0	2721.51	2721.51
SS 10	878.01	1062.85	1940.86	0.00	527.35	527.35	0	694.28	694.28
Sum	3930.33	42,296.29	46,226.62	857.23	22,156.50	23013.73	1241.41	29,796.36	31,037.77

Table 7. Summary of the joint simulation of dams: La Angostura and Malpaso: **deficit**.

Simulation	**Test 1**			**Test 2**			**Test 3**		
	Deficit [hm^3]			**Deficit [hm^3]**			**Deficit [hm^3]**		
	La Angostura	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**
SS 1	0	0	0	0.00	0.00	0.00	0	0	0
SS 2	0	0	0	0.00	0.00	0.00	0	0	0
SS 3	881.25	0	881.25	1459.55	0.00	1459.55	1126.21	0	1126.21
SS 4	4330.95	0	4330.95	4608.81	648.98	5257.79	4284.27	231.94	4516.21
SS 5	0	0	0	0.00	0.00	0.00	0	0	0
SS 6	0	0	0	0.00	0.00	0.00	0	0	0
SS 7	0	0	0	0.00	0.00	0.00	0	0	0
SS 8	0	0	0	789.36	0.00	789.36	210.30	0	210.3
SS 9	0	0	0	0.00	0.00	0.00	0	0	0
SS 10	0	0	0	618.18	0.00	618.18	0	0	0
Sum	5212.2	0	5212.2	7475.9	648.98	8124.88	5620.78	231.94	5852.72
Maximum Deficit in Malpaso		0			648.98			231.94	

Tables 8–10 compare the results obtained from the generation of 10 synthetic series with 1000 years of record each with those obtained during the simulation of the historical record.

Table 8. Long-term total energy comparison: 10 synthetic series vs. historical record.

Energy Generated [GWh/Fortnight].			
Policy	**Test 1**	**Test 2**	**Test 3**
Average of 10 synthetic series of 999 years * c/u	477.94	471.18	473.23
Average historical record of 61 years **	477.21	470.38	472.29
Relative difference [%]	0.04	0.17	0.20

Note: * and ** the first year was neglected due to initial instability in reservoir function.

Table 9. Comparison of total spillage: 10 synthetic series vs. historical record.

Spill, [hm^3]						
Dam	**Synthetic Series**			**Historical Record**		
	Test 1	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
La Angostura	3930.33	857.23	1241.41	0	0	0
Malpaso	42,296.29	22,156.5	29,796.36	0	0	0
Total	46,226.62	23,013.73	31,037.77	0	0	0

Table 10. Comparison of total deficit: 10 synthetic series vs. historical records.

Deficit, [hm^3]						
Dam	**Synthetic Series**			**Historical Record**		
	Test 1	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
La Angostura	5212.2	7475.9	5620.78	0	0	0
Malpaso	0	648.98	231.94	0	0	0
Total	5212.2	8124.88	5852.72	0	0	0

Table 8 shows a great similarity between the average values corresponding to the historical series and those corresponding to the synthetic series, which confirms the validity of the method used to generate the latter.

As expected, the policies (trials) with the highest energy generation correspond to those with the highest storage and are the most prone to spills.

According to the magnitude of the deficit (Table 10), it is observed that:

- In Test 1, there was no deficit at Malpaso dam and the smallest deficit at La Angostura dam.

  It is the best trial in terms of avoiding deficit events at both dams;
- Test 2 is the trial with the largest deficits in both dams.

By developing synthetic series longer than the historical record and simulating the behavior of the policies corresponding to each test, it is possible to visualize the behavior of the spills and deficits during the simulation, presenting results that could not be visualized with the historical series because of the few years of simulation.

The results of the synthetic series allow us to count the magnitude and frequency of spills and deficits, which are associated with periods of abundance and scarcity for the system. Figures 9 and 10 show the spills and deficits of the 10 synthetic series, for each test carried out, ordered from highest to lowest, obtaining their absolute frequency and magnitude for La Angostura and Malpaso dams.

For spills, Figure 9 shows that the highest frequency occurs at flows of 200 to 400 m^3/s, which is an advantage of using the guide curves, since all policies avoid the frequency of high spills. In La Angostura dam, the maximum spills occur between 1200 to 1400 m^3/s, while in Malpaso dam, they increase from 1800 to 2000 m^3/s; however, the frequency at these flows is very low.

The long-term deficits (see Figure 10) present a very low probability of occurring at Malpaso Dam with almost all policies, except with the policy of trial 1, wherein no deficits occur in the simulated 10,000 years.

In La Angostura dam, the maximum probability of occurrence is 16/10,000 years with a magnitude of 150 to 200 m^3/s. In each of the simulated policies, although the probability is very low, the possibility of having deficits in La Angostura is higher than in Malpaso dam.

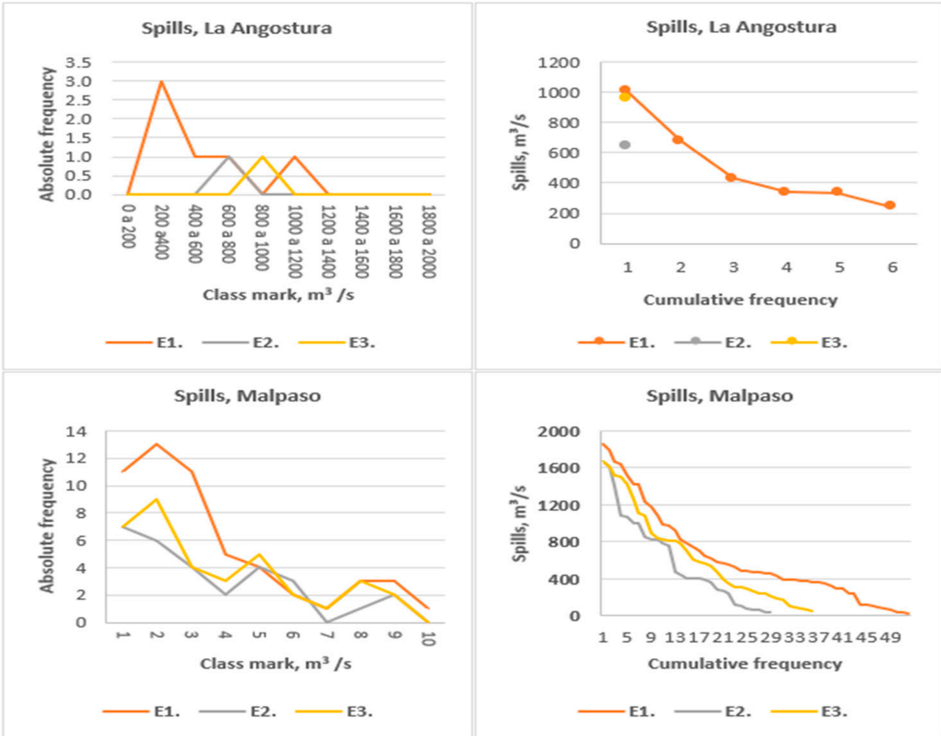

Figure 9. Spill count in the policies tested for La Angostura dam and Malpaso dam.

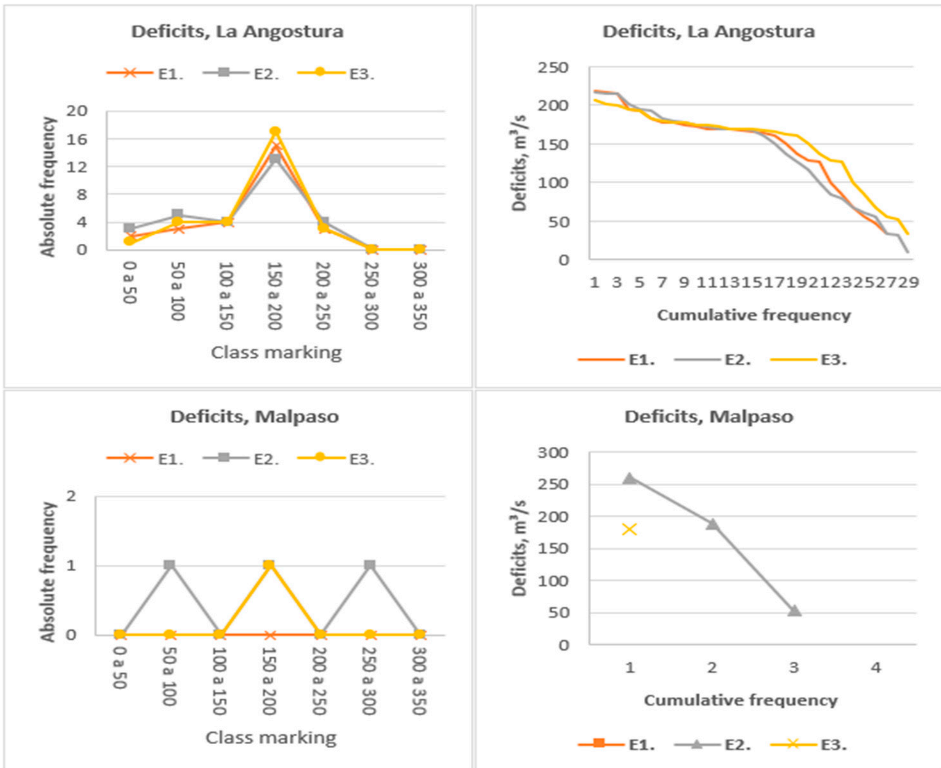

Figure 10. Deficit count in the policies tested for La Angostura dam and Malpaso dam.

5. Discussion

Upon analyzing the results obtained in the long-term simulation of Tests 1, 2, and 3, it was observed that in all cases, the spills in Malpaso were much greater than those in La Angostura. Considering also that the spills in Malpaso produced more damage to the population, a new trial called Test 4 was proposed in which the guide curve of Malpaso would be the lowest of those tested, that is, the guide curve of Test 2, and, in La Angostura, the guide curve corresponding to Test 1 would be tested (see Figure 11). The main results obtained are presented below (Tables 11–13).

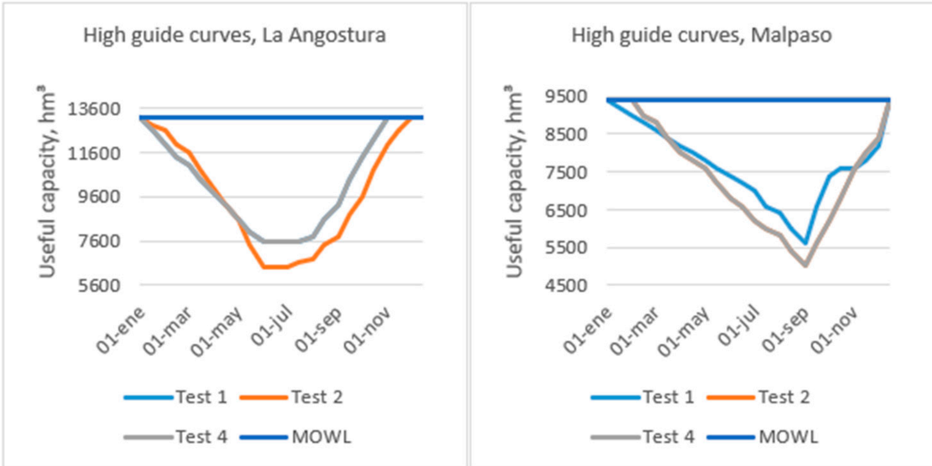

Figure 11. Guide curves tested for the policy with the combined guide curve, Test 4.

Table 11. Comparison of total deficit: 10 synthetic series vs. historical records.

Simulation	Test 1			Test 2			Test 4		
	Energy Generated [GWh/Fortnight].			Energy Generated [GWh/Fortnight].			Energy Generated [GWh/Fortnight].		
	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total	La Angostura	Malpaso	Total
SS 1	277.32	198.96	476.28	276.39	193.1	469.48	277.17	195.19	472.36
SS 2	278.5	200.23	478.73	277.62	194.41	472.04	278.36	196.50	474.86
SS 3	275.91	198.76	474.67	274.96	192.97	467.93	275.76	195.00	470.76
SS 4	280.61	199.79	480.4	279.7	193.96	473.66	280.51	196.06	476.58
SS 5	275.12	196.79	471.91	274.23	191.03	465.26	274.99	193.05	468.04
SS 6	283.01	202.04	485.05	282.03	196.12	478.15	282.85	198.22	481.07
SS 7	279.62	200.43	480.05	278.66	194.6	473.26	279.47	196.67	476.14
SS 8	279.28	201.13	480.4	278.31	195.24	473.55	279.12	197.35	476.47
SS 9	276.64	198.09	474.73	275.72	192.27	467.99	276.50	194.36	470.86
SS 10	278.5	198.71	477.21	277.58	192.89	470.47	278.34	194.95	473.30
Average/999 Years *	278.45	199.49	477.94	277.52	193.66	471.18	278.31	195.74	474.04
AverageHist/61 Years *	277.68	199.53	477.22	276.69	193.69	470.38	277.57	195.72	473.29
Relative Difference [%]	0.28	0.02	0.04	0.3	0.15	0.17	0.27	0.01	0.16

Note: * Excluding the first year of simulation.

Table 12. Comparison of spills during the long-term simulation of the 10 synthetic series.

Simulation	Test 1			Test 2			Test 4		
	Spill [hm^3]			Spill [hm^3]			Spill [hm^3]		
Dam	**La Angostura**	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**
SS 1	0	588.81	588.81	0.00	0.00	0.00	0	0	0
SS 2	2493.03	14,124.63	16,617.66	857.23	7515.74	8372.97	2365.61	9817.69	12,183.3
SS 3	0	8956.77	8956.77	0.00	4573.96	4573.96	0	5443.72	5443.72
SS 4	0	5517.34	5517.34	0.00	2843.52	2843.52	0	2916.18	2916.18
SS 5	559.29	2341.17	2900.46	0.00	1292.29	1292.29	171.96	1615.13	1787.09
SS 6	0	2715.2	2715.20	0.00	1828.20	1828.20	0	2096.7	2096.7
SS 7	0	2972.39	2972.39	0.00	1512.09	1512.09	0	1943.73	1943.73
SS 8	0	0	0.00	0.00	0.00	0.00	0	0	0
SS 9	0	4017.13	4017.13	0.00	2063.35	2063.35	0	2748.8	2748.8
SS 10	878.01	1062.85	1940.86	0.00	527.35	527.35	863.5	278.91	1142.41
Sum Spill	3930.33	42,296.29	46,226.62	857.23	22,156.50	23,013.73	3401.07	26,860.86	30,261.93

Table 13. Comparison of deficits during the long-term simulation of the 10 synthetic series for the three tests.

Simulation	Test 1			Test 2			Test 4		
	Deficit [hm^3]			Deficit [hm^3]			Deficit [hm^3]		
	La Angostura	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**	**La Angostura**	**Malpaso**	**Total**
SS 1	0	0	0	0	0	0	0	0	0
SS 2	0	0	0	0	0	0	0	0	0
SS 3	881.25	0	881.25	1459.55	0	1459.55	934.76	0	934.76
SS 4	4330.95	0	4330.95	4608.81	648.98	5257.79	4351	626.69	4977.69
SS 5	0	0	0	0	0	0	0	0	0
SS 6	0	0	0	0	0	0	0	0	0
SS 7	0	0	0	0	0	0	0	0	0
SS 8	0	0	0	789.36	0	789.36	60.72	0	60.72
SS 9	0	0	0	0	0	0	0	0	0
SS 10	0	0	0	0	0	0	0	0	0
Sum Deficit	5212.2	0	5212.2	7475.9	648.98	8124.88	5346.48	626.69	5973.17

Table 12 shows the spill presented in Test 4 and the summary of Test 1 and 2. Table 12 shows that:

(a) The values of the high guide curves used in Test 1 are those that maintain higher storage levels in the two dams, thus generating fewer deficits. Test 2, by considering lower levels in the reservoirs, leads to the lowest volume spilled in the system, totaling 23,014 hm^3, of which 96% corresponds to Malpaso and the rest to La Angostura. Test 4 is a combination of the values. The guide curve of Test 1 for La Angostura and that of Test 2 for Malpaso maintain practically unchanged volume spilled in the 10 synthetic series in La Angostura with Test 1 (530 hm^3 less), but in Malpaso, it manages to reduce the spill by 15,435 hm^3, that is, a little more than a third of the volume spilled obtained for Test 1, although it still presents a spill 18% higher than that of Test 2;

(b) In the three tests, it is observed that the greatest magnitude of the spill event always occurs in Malpaso; however, in Test 4, the proportion of spills in Malpaso with respect to the total is considerably reduced, from 96% in Test 2 and 94% in Test 1, to 87%;

(c) In the case of La Angostura, Test 1 presents the greatest spill of the three trials compared, while Test 4 manages to be a little below. However, in this case, the Malpaso dam would be available to regulate this spilled volume.

It can be seen from Table 13 that:

(a) At the system level, the simulation with the lowest deficits is Test 1, followed by Test 4 and Test 2;

(b) In the case of La Angostura dam, a deficit event occurs in all four trials. In Test 1, the event occurs in 2 of the 10 series; in Test 4, the event occurs in 3 series; and in Test 2, the event occurs in 4 of the 10 series. The magnitude of these deficits is small, except in the case of series 4, where it is practically the same for Test 1 and 4 but increases in Test 2;

(c) For Malpaso, Test 1 shows no deficit. Tests 2 and 4 present the event only in series 4 and with relatively small values.

Contrary to the spill event, the largest magnitude of the deficit event always occurs in La Angostura.

In Figures 12 and 13, the frequency of spills and deficits were counted using the policy of Trial 4 with the combined guide curve. In the Malpaso Dam, the frequency of spills between 0 and 200 m^3/s increases and the frequencies decrease for higher spills, with values very close to those of Test 2.

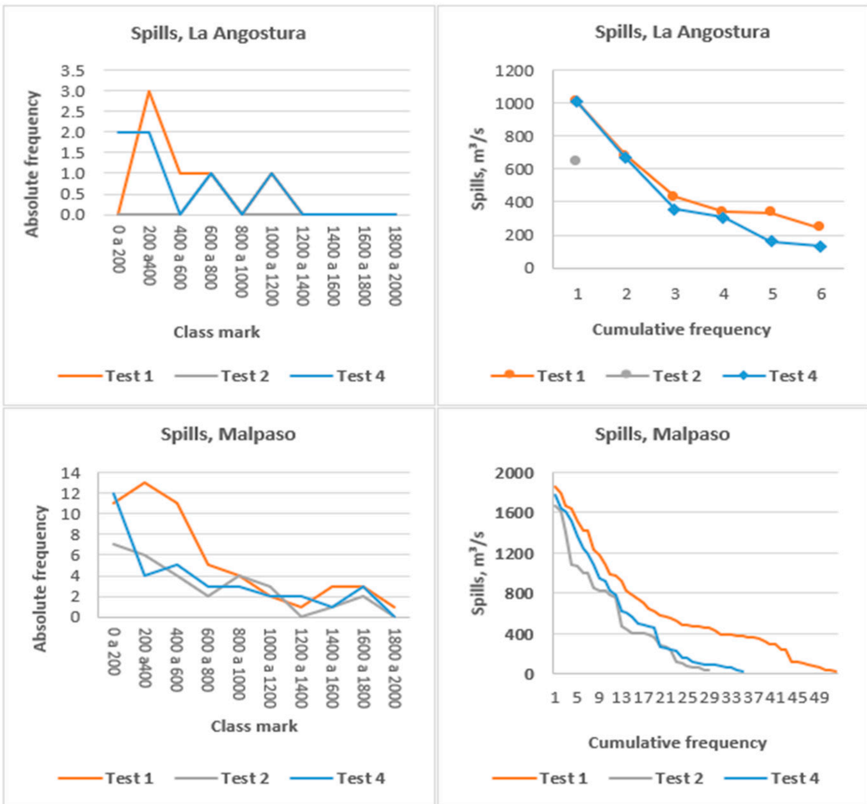

Figure 12. Spill count with the combined guide curve policy.

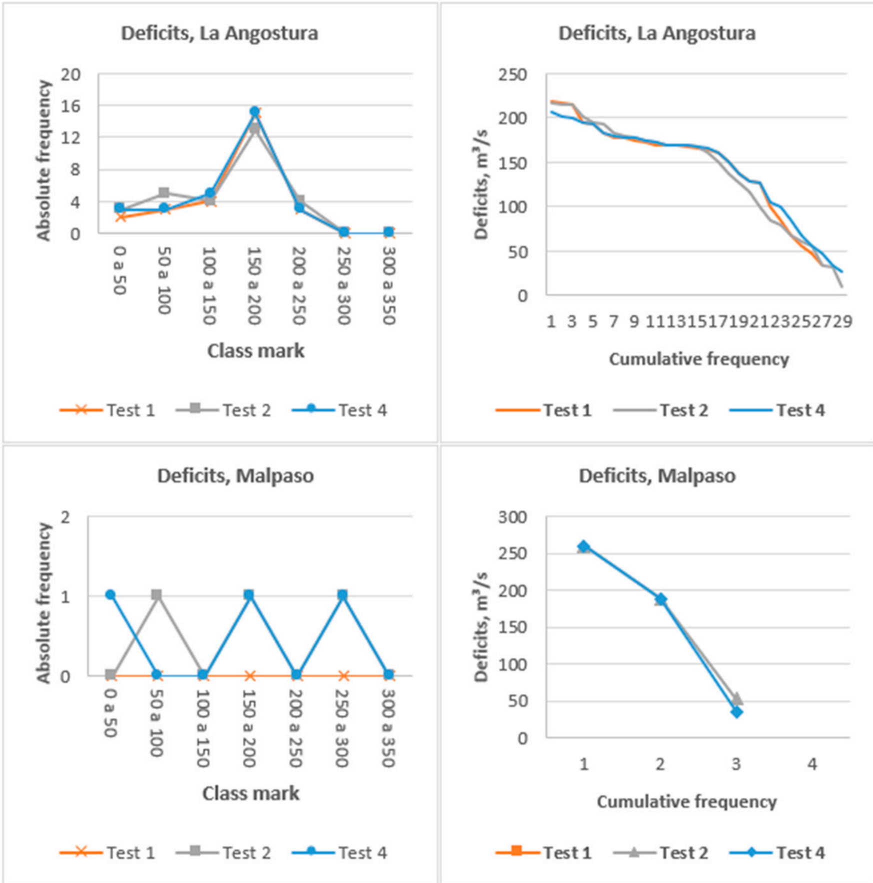

Figure 13. Deficit count with the combined guide curve policy.

6. Conclusions

A simulation of a system of four dams with different optimal policies, obtained with dynamic programming and the use of guide curves, did not produce spillage or deficits in the system analyzed; therefore, we decided to simulate the behavior of the system considering more critical events, which were estimated from a generated synthetic series.

The synthetic series was generated using the Svanidze method, with some modifications proposed in this work, in order to preserve the statistical characteristics of the historical record, including the cross-correlation between the inflows to the two reservoirs of the Grijalva System, and at the same time, produce extreme events that allowed us to assess the behavior of the dam system in the face of such events.

The use of synthetic inflow volumes series longer than the historical record to carry out simulations of optimal operation policies that include the use of guide curves proved to be an efficient tool for the evaluation of the behavior of such policies, since it allowed for the identification of events of greater magnitude than those that occurred historically in the analyzed reservoir system.

The most notable thing that was observed when simulating, with synthetic records, the behavior of the policies obtained in Tests 1 and 2 is that the spills from Malpaso were much greater than those from La Angostura. So, taking into account that the spills from Malpaso were much more detrimental than those from La Angostura, a new combination of guide curves was proposed (which was called policy Test 4), which consisted of using the guide curve proposed in Test 1 for La Angostura and the one proposed in Test 2 for Malpaso.

The results of the simulation with the Test 4 policy and the synthetic records showed that, although spills from La Angostura increased, those from Malpaso were considerably reduced with respect to those obtained with the Test 1 policy, and only marginally increased with respect to those obtained with Test 2.

Another novelty of the procedure used was the increase in the dimensionality of the problem when considering the year divided into seven stages (in previous studies, six stages were used), in addition to the fact that the volume increment of ΔV = 200 hm^3 considered was lower than the ΔV = 600 hm^3 previously used, which increased the number of states (NS) of the problem. These considerations provided results with greater detail regarding the optimal extractions. Furthermore, the inclusion in the objective function of the quantification of the volumes outside the guide curves was another contribution in this research.

Author Contributions: Conceptualization, R.D.-M. and M.L.A.-J.; methodology R.D.-M., M.L.A.-J., R.V.-E., and R.M.-R.; validation, R.V.-E., data curation, R.V.-E., E.J.-D., J.O.-R., and E.C.-E.; writing—review and editing, M.L.A.-J., A.M.-R., E.J.-D., and R.D.-M.; visualization, R.D.-M.; supervision, M.L.A.-J. and R.D.-M. All authors have read and agreed to the published version of the manuscript.

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