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WATER SUPPLY OPERATING RULES IN PARALLEL DAMS BY MEANS OF GENETIC ALGORITHMS

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ABSTRACT

The Cutzamala System is the most important piece of water infrastructure that the State of Mexico has brought to the center of Mexico region and aims to provide at least 16 m^3/s of water to the capital since 1974. The system consists of the Tuxpan and El Bosque dams, located in the state of Michoacan and the Ixtapan del Oro, Villa Victoria, Valle de Bravo, Chilesdo and Colorines, in the State of Mexico. In this study monthly operating policies obtained to satisfy the growing demand for potable water using three of the most important dams in the system: El Bosque, Valle de Bravo and Villa Victoria, operating in parallel. Evolutionary algorithms were used, namely Genetic Algorithms to assess in an objective function that seeks to maximize the extractions for human uses, and minimize by imposing penalties, the presence of spills and deficits in the system. Operation of the system with well defined rules of operation was simulated using the historical record of inflow volumes from 1994 to 2011. The optimal policy found concile the objectives achieved.

INTRODUCTION

The Cutzamala system is the México's most important water supply work, consists of three storage dams: Villa Victoria, Valle de Bravo and El Bosque and four diversion dams: Tuxpan, Ixtapan del Oro, Colorines and Chilesdo which are located in Michoacan and Mexico States (Figure 1). The system provides a design flow of 19 m^3/s to supply drinking water to the Metropolitan Area of the Valley of Mexico and Toluca.

The system operation is complex because it must concile different objectives, first to extract as much of the reservoirs, but without condition of deficit or spills on them.

This paper reviews the historical performance of El Bosque, Valle de Bravo and Villa Victoria dams, that operates in parallel. With the information obtained from this review it was proposed to obtain optimal extraction policies for the three dams of the system using genetic algorithms, which have been used since the mid-eighties of the twentieth century and whose recent applications in hydrology and Power is highlighted in the work of Huang *et al.*, 2002 [1], Zhang *et al*., 2009 [2], Dominguez *et al*., 2012 [3], among others. The obtained polices were probed using a simulation program designed by the staff of the Institute of Engineering of the National Autonomous University of Mexico which consideres the operation of three dams in parallel.

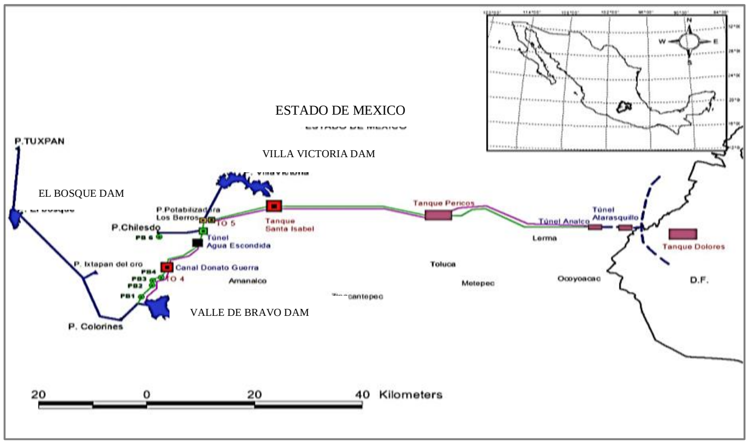

Figure 1. System Cutzamala River dams

METHODOLOGY

GENETIC ALGORITHMS

Genetic algorithms (GA) are a branch of evolutionary computation, originally conceived by John Holland (Holland, 1975 [4]), part of the bio-inspired algorithms and optimization tool very handy in the twentieth century became the mid-eighties and as personal computers have become faster. Its application in the case of hydrology and hydraulics became more noticeable in the first decade of this century.

The fundamental characteristic of the GA is the use of an operator of recombination or crossover, as a vehicle to search, and a reproduction algorithm proportional to the performance; is generally represented by the structure presented in Figure 2, the operator used in the application are selection, sharing or cross and mutation. The selection can be done by the roulette method, the stochastic universal or tournament (Goldberg , 1989 [5]). The exchange is in binary level but can also be in a real number level; the mutation may or may not be considered, and allows individuals appear in a new generation.

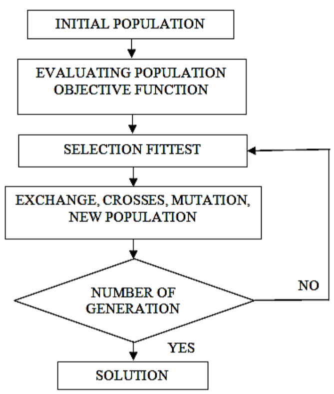

Figure 2. Block diagram of a GA

In this study, individuals correspond to sets of four parameters that defines the coordenates of two points of the annual extractions curve from the analyzed reservoir system (Figure 3); in a first analysis, three trials where made fixing the annual extraction percentage for each dam, obtained from the historical extraction for each dam; the extrations curve shows the total annual storages in October against the total annual extractions for the three analyzed dams. In a second analysis, besides this four parameters, the percentages of annual extraction to be assign at each dam were considered (the algorithm takes into account that the sum of these percentajes may represent the 100%). Therefore for these four latest trials there were seven unknowns. The objective of this problem was to optimize the extrations for each dam, with a minimum of spills and deficit in the system.

OBJECTIVE FUNCTION

In tests 1 to 3 the objective function (FO) was to maximize the extractions by imposing penalties for spill or a deficit condition in the system, that is:

$$FO = Max\left\{c_e * V_e - c_{der} V_{derr} - c_{def} V_{def}\right\} \tag{1}$$

Where, for the simulation period of n years, V_e is the total volume of extractions in the three dams, V_{derr} is total volume of spills of the three dams, V_{def} is the total volume of the deficit of the three dams, c_e is a weight coefficient for extractions, c_{der} is a penalty coefficient for the case of a spill, c_{def} is a penalty coefficient for the event of deficit.

Because in tests 4 and 5 percentages of extraction of each dam are left free, in the FO it was added the restriction that the sum of the percentages of annual extraction from the three reservoirs must be equal to 1, so it is penalized the offset to one of the sum of the percentages of annual extraction, thereby leaving the equation for the FO as follows:

$$FO = Max\left\{c_e * V_e - c_{der} V_{derr} - c_{def} V_{def} - c_{err} Err\right\} \tag{2}$$

Where: $Err = 1 - \sum_{i=1}^{3} p_i$, pi is the annual extraction percentage for the dam i, i = 1,2,3; c_{err} is a penalty factor to minimize the value of Err.

SYSTEM OPERATION SIMULATION

The system operation simulation is made with the continuity equation for a system of three reservoirs in parallel:

$$(S_{j,i+1} = S_{j,i} + I_{j,i} - O_{j,i}) \tag{3}$$

Where: i is the time interval considered (in this case months), j is the subscript corresponding to each dam, Sj, i +1 is the volume of final storage, Sj,i is the volume of initial storage, Ij,i are the inputs to the reservoir (basin itself considered for each reservoir) and Oj the total output obtained by the following equation.

$$O_i = Evni + Vei \tag{4}$$

Where *Evni* is the net evaporation obtained with the historical values of precipitation minus evaporation, *Vei* is the monthly volume of extraction obtained from the operation policy (herein curve Z) as shown in Figure 3 and the considerations of monthly extractions percentajes for each dam. In this study a monthly extraction porcentaje for each dam was considered equal to 1/12

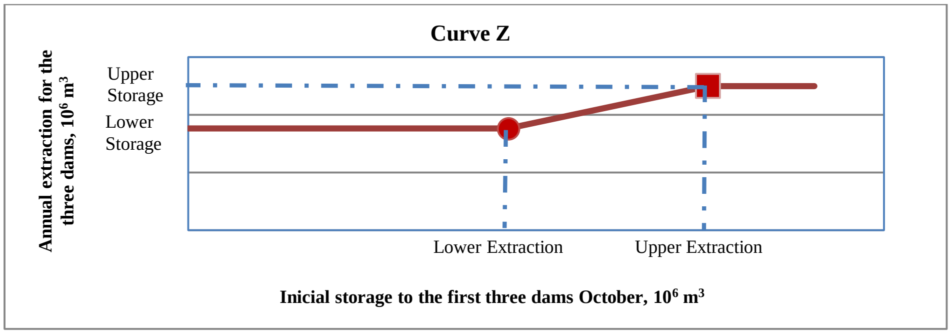

Figure 3. Curve Z (Operation policy)

Table 1. Overview of parameters limits

Millions m^3	Lower limit				Upper limit			
	Initial Vol Storage	Initial Extrac	Final Vol Storage	Final Extrac	Initial Vol Storage	Initial Extrac	Final Vol Storage	Final Extrac
Test 1	100	100	400	200	459.8	352.7	747.2	500
Test 2 to 7	100	250	400	350	459.8	352.7	747.2	500

The simulation program was coded in Fortran language and the executable program is called by the genetic algorithm to evaluate the objective function for each individual in each generation.

INPUT DATA

For the simulation of the system operation we considered the inflow to El Bosque, Valle de Bravo and Villa Victoria dams in the common period of 1994 to 2011. Additionally it was made a review of the historical operation to get the approximate percentages of the extraction volumes that have been allocated annually to the dam system; we obtained the depth of the net evaporation monthly average with the years and months available. With the data of elevations-capabilities-areas curve of the reservoirs we plot trend lines to obtain the storage and the area in function of the elevation (Figures 4 and 5).

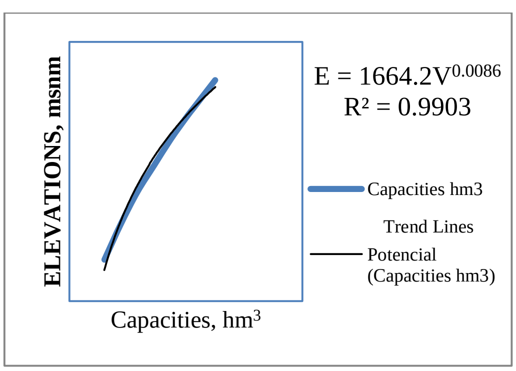

Figure 4. Elevations - Capacities Curve

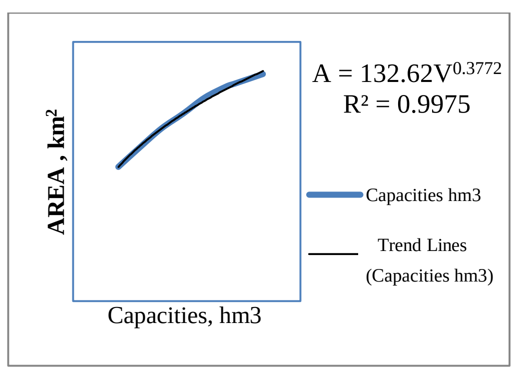

Figure 5. Elevations - Areas Curve

For the genetic algorithm we consider 200 individuals and 500 generations; the limits of the search range for the parameters are listed in Table 1. Different penalty coefficients were tested (Table 2).

Table 2. Penalty coefficients

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
C_e (por extracc)	1	1	1	1	1	1	1
C_{derr}	10	10	100	100	100	100	1,000
C_{def}	1,000	1,000	1,000	1,000	1,000	1,000	1,000
C_{err}				1,000	10,000	100,000	100,000

APPLICATION AND RESULTS

The results of the seven tests are presented in Table 3.

Table 3. Results of the genetic algorithm by attaching a simulation program for operating a three paralle dam system

	Dam 1				**Dam 2**			
	Extraction	**Spill**	**Deficit**	**Min Storage**	**Extraction**	**Spill**	**Deficit**	**Min Storage**
Test	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3
1	2822.19	181.38	0.00	60.00	2147.32	1404.59	0.00	375.18
2	2869.52	145.82	8.68	60.00	2183.33	1368.58	0.00	374.51
3	2898.10	122.18	12.89	60.00	2205.08	1346.83	0.00	374.51
4	2774.30	201.64	10.75	60.00	3613.70	275.05	10.91	50.00
5	3311.70	80.94	366.56	60.00	3549.00	310.21	0.00	81.35
6	2552.40	415.81	0.00	76.17	3295.80	409.28	0.00	230.07
7	2712.60	273.97	0.00	65.25	3324.60	392.86	0.00	217.83

Table 3.1. Continuation

	Dam 3				**<u>Total</u>**			**FO $_{ec\ 1}$**	**FO $_{ec\ 2}$**
	Extraction	**Spill**	**Deficit**	**Minim Storage**	**<u>Extraction</u>**	**<u>Spill</u>**	**<u>Déficit</u>**		
Test	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3		
1	1165.69	423.40	0.00	127.41	6135.20	2009.37	0.00	139.59	
2	1185.24	405.06	0.00	126.34	6238.09	1919.46	8.68	216.37	
3	1197.04	393.53	0.00	126.31	6300.22	1862.54	12.89	1928.44	
4	1687.30	1.62	29.89	30.00	8075.30	478.31	51.55	913.06	918.80
5	1657.60	7.45	0.00	30.00	8518.30	398.60	366.56	3979.02	3981.15
6	1551.60	99.31	0.00	82.38	7399.80	924.40	0.00	850.40	857.70
7	1560.60	92.88	0.00	80.09	7597.80	759.71	0.00	7521.12	7626.17

From this table it is observed that with the objective function of Equation 1, the extraction and deficit increases from tests 1 to 3, but the spill decreases. In tests 4 to 7 where the objective function of Equation 2 is applied, test 4 and 5 behave with the same trend line as test 1 to 3. In test 6 a greater penalty is added for the error term of the objective function, in order to reduce deficits until they become zero, but even the maximum extraction and spill is high. In test 7 wherein the coefficient is increased to penalize the spill so that the optimal values are achieved with a greater extraction, minor spill, compared to test number 6, and no deficit.

By considering all these results, the test 6 was considered the best one because the sum of the percentages of extraction was the closest to 1 with respect to the other test (Table 4). Operating policies (curves Z) of all test were plotted in Figure 6.

Table 4. Annual percentage extractions for each dam

Dams	**Test 4**	**Test 5**	**Test 6**	**Test 7**
%P1 (EB)	0.37	0.34	0.35	0.37
%P2 (VB)	0.48	0.44	0.45	0.45
%P3 (VV)	0.22	0.21	0.21	0.21
Sum	1.0758	0.9854	1.0085	1.0324

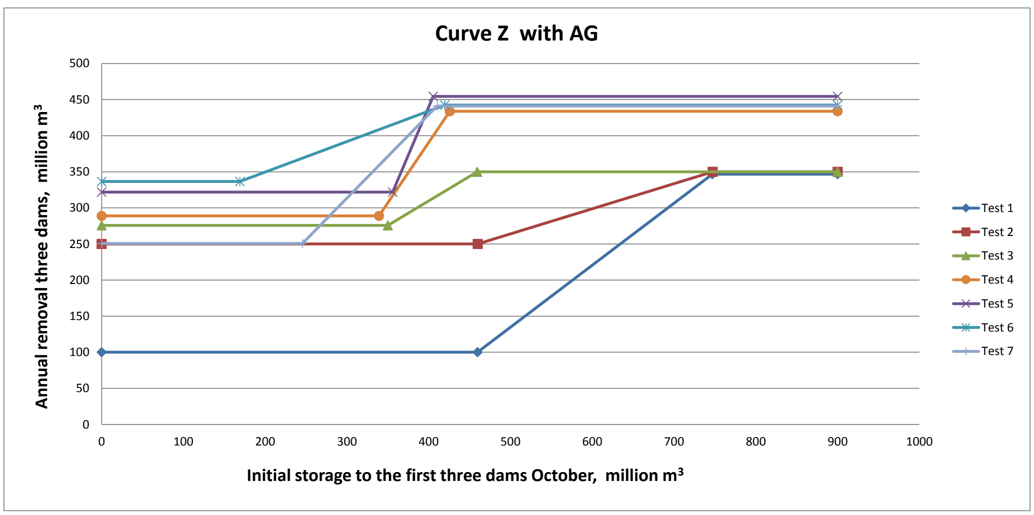

Figure 6. Curves Z with the results of 7 test

In the review of the historical performance period of the analyzed years, 8,011.110 millions m^3 of total extractions were found in the system, 541.42 millions m^3 of total spills and a total deficit of 195.05 million m^3, so if the policy operation 6 had been used, it would had been a better operation but with slightly smaller extraction (7,399.80 million m^3), spill increases (924.40 million of m^3) and there is no deficit.

A comparison of the extraction's performance, the spill and the deficit during the historic operation against the simulated policy 6 is presented in Figures 7-9.

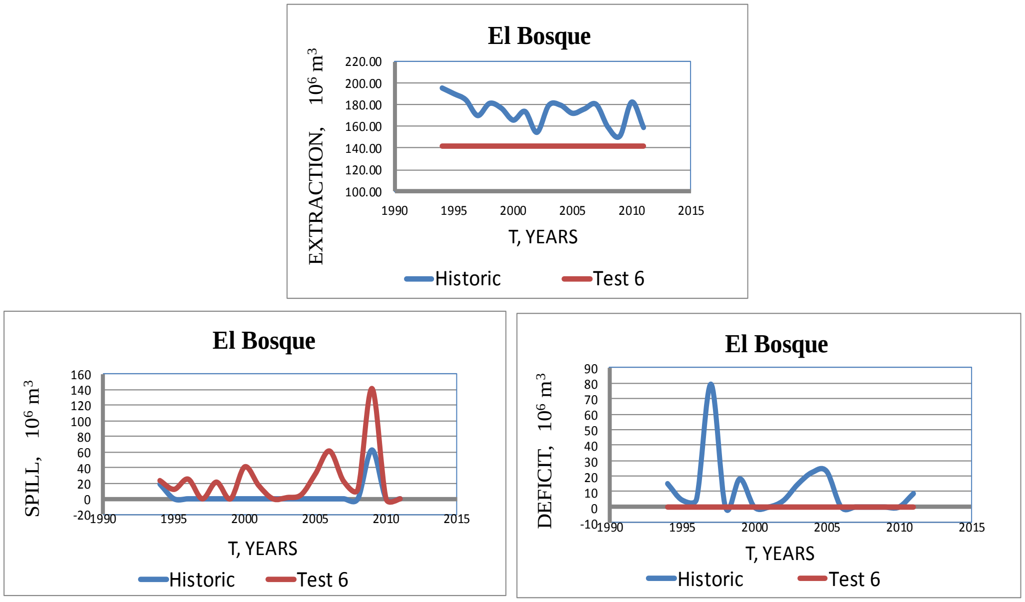

Figure 7. Extraction, spill and deficit simulated and historical. El Bosque Dam. Test 6

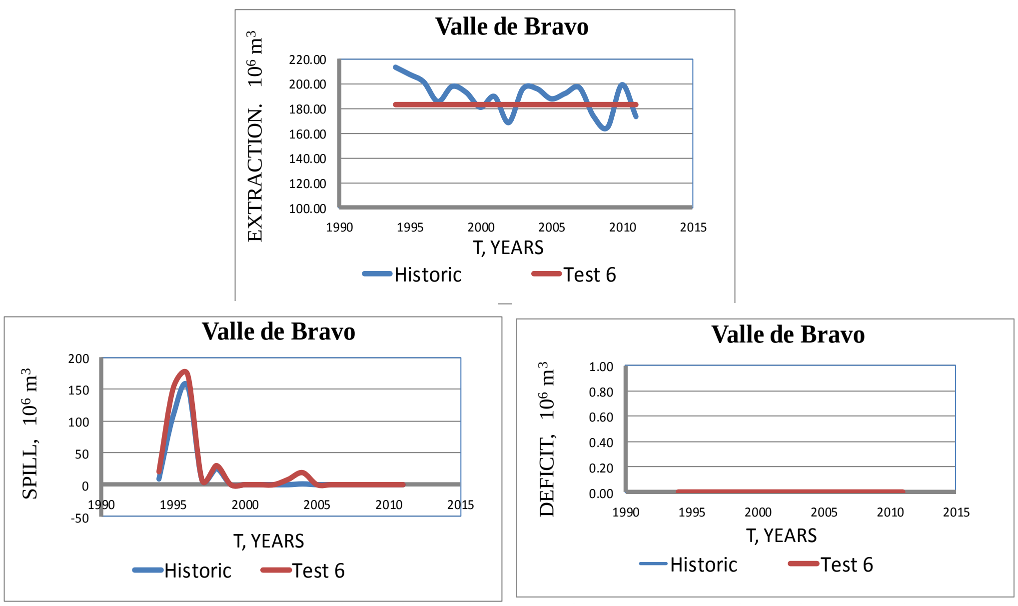

Figure 8. Extraction, spill and deficit simulated and historical. Valle de Bravo Dam. Test 6

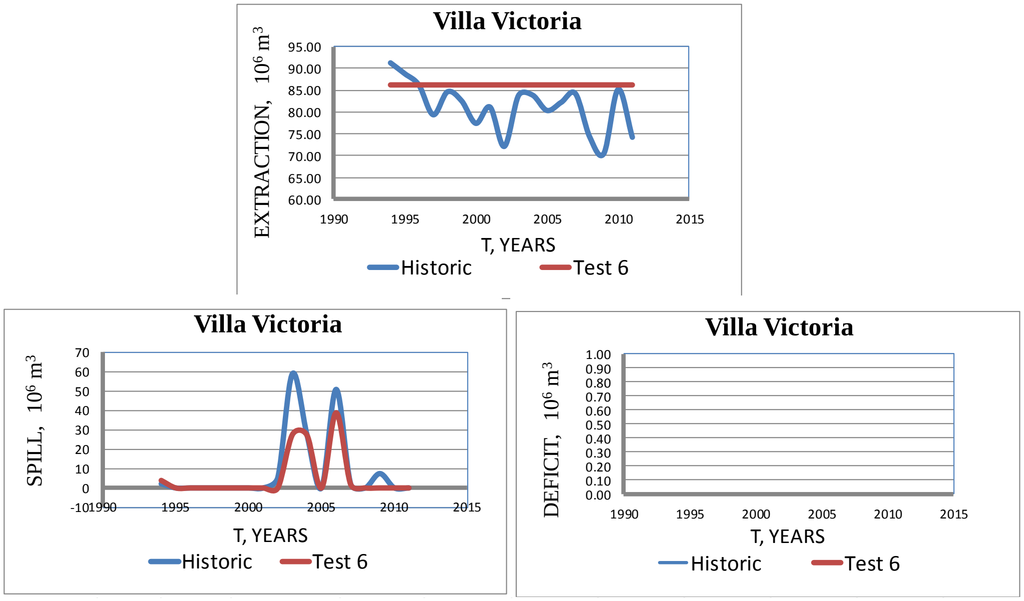

Figure 9. Extraction, spill and deficit simulated and historical. Villa Victoria Dam. Test 6

CONCLUSIONS AND RECOMMENDATIONS

The use of genetic algorithms, in combination with a simulation program for the operation of a three dams system in parallel, lead to determinate optimal extraction policies for water supply purposes in the three dams system of Cutzamala River.

The Policy obtained with test 6 allowed to maximize total extractions in the system (7,399.80 million m^3) with minor spill (924.40 million m^3) and no deficit for the three dams. It was determined also that from El Bosque dam should be extracted 35% of the total annual extraction, from Valle de Bravo 45% and from Villa Victoria 21%. Altough for these policy the extraction is lower by 7.63% compared with the total historical extraction, we achieved the goal to obtain the lowest possible spill and no deficit for the Cutzamala's three dams system.

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