Water Supply Operating Rules in Parallel Dams by Means of Genetic Algorithms

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Abstract: *The Cutzamala system is the work of urban water infrastructure most important of Mexico since 1974, because it supplies drinking water to the Metropolitan Area of Mexico City with a flow rate of approximately 16 m^3/s. The main dams of the Cutzamala system are: El Bosque, located in MIchoacan State; Valle de Bravo and Villa Victoria in the State of Mexico. In this analysis it was considered a parallel operation of these dams, i.e. independently feeding the water treatment plant Los Berros. A historical review was carried out considering, at each year, constant monthly extractions for each storage dam, genetic algorithms were then used to evaluate an objective function which maximize the extractions and minimize, by means of penalty coefficients, the presence of spills and deficits in the system. Finally, the obtained operating rules where simulated, using the historical record of input volumes by basin in the period 1994-2011. The use of genetic algorithms, engaging a simulation program of the operation of a system of three parallel dams, led to the identification of optimal policies of removal, for purposes of potable water for human consumption in the Cutzamala River system. The optimal operating rule successfully allowed reconciling the objectives.*

Keywords: *Cutzamala System, Genetic Algorithms, Operating Rules, Drinking water.*

1. Introduction

Countries suffering moderate water stress have less than 1700 cubic meters of water per person per year. This means that water is not often available at certain times of the year in certain places, which produces a hard choice to make between personal consumption, agriculture or industry. [1]
Nowadays the water of reservoirs created by dams provide a pool of water that guarantees reliable supply to the population, this promotes better human conditions. Actually, it has become a key priority find a way to optimize the work performance of a system in terms of energy efficiency and a good water supply network. [2]
The decision to bring water from basins located outside the Valley of Mexico was due to the impacts caused by the sinking of the city by the extraction of groundwater. The excessive growth of population during the thirties, became apparent that groundwater sources are insufficient to meet the demand of thousands of new residents. It should be mentioned that the basin where the Mexico City and its metropolitan area is located, it is surrounded by five basins, being Lerma and Cutzamala nearby basins. The other three are Amacuzac, Libres Oriental and Tecolutla River. Of these, the first two were more appropriate to become the first contributors of water to the Mexico City. [3]
The Cutzamala system is the most important work of urban water infrastructure of the country's central portion since 1974, due to it supplies of potable water to Mexico City Metropolitan Area (MCMA) with a flow of approximately 16 m^3/s [4]. The dams of the Cutzamala system are Tuxpan and El Bosque located in the state of Michoacan, Ixtapan Del Oro, Colorines, Valle de Bravo, Chilesdo and Villa Victoria in the State of Mexico [5], as shown in the diagram of Figure 1. [6]
The drinking water supply was recognized as one of the major challenges that will determine the sustainability in Mexico City [7]. Currently It shows obvious signs of degradation, lack of investment, and reduction in the capacity of the system. The effects of climate change need to be evaluated in order to determine its impact and promote strategies that enable us to deal with this challenge.

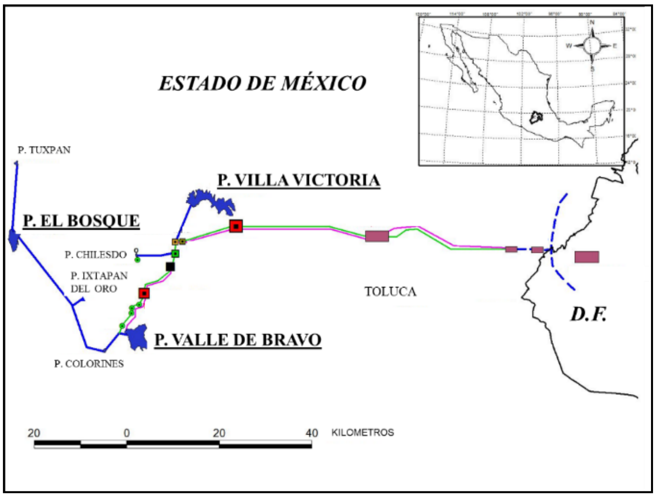

Fig. 1. Cutzamala System Diagram

The system deliveries water with an estimated efficiency of 60 %, the flow which doesn't get to be delivered is attributed to the leak along the pipelines [7], would be proposed to revise the losses caused by the system in order to achieve the required performance, there is a need not only adequate static and dynamic parameters, but also a modern concept diagram of a hydrostatic transmission work [8]; it is believed that part of the problem can also be due to the policies of operation of the dams in the system. If such policies will be modified the operation of the whole system, it could be improved and thus to achieve better extractions, avoiding deficits or decrease them as much as possible, while ensuring that spills do not occur in these dams, by all those reasons the operation of the system is complex.
Currently the estimated supply for the Metropolitan Area is an average flow of 59.9 m^3/s divided between various sources that are shown in Table 1.

TABLE 1: Water supply to the MCMA

Infrastructure	Supply (m^3/s)	% to input
Aquifer MCMA	39.00	65 %
Cutzamala System	**14.70**	**25 %**
Lerma System	4.80	8 %
Madín Dam	1.40	2 %

With the historical review of the system operation it is intended to investigate the possible lack of operating rules. It is important to notice that, in the analysis, it was assumed that the system works in parallel, that means that the dams: El Bosque, Valle de Bravo and Villa Victoria will catch their own inflow and their outputs or extractions will arrive directly to the Water Treatment Plant Los Berros. [9].
As mentioned, there is no complete data of the four diversion dams: Tuxpan, Ixtapan del Oro, Colorines and Chilesdo; so it only took into account the three major dams and were considered to be able to take one hundred percent of the delivered volume to the Metropolitan Area of Mexico's Valley (MCMA).
Another hypothesis considered in the operation of the reservoirs was to assume a constant monthly extraction at each year for the three dams.

2. Background

Nowadays, drinking water supply represents one of the most important priorities, so it is important to attend the new demands and gradually reduce the over- exploitation to which has been subjected the aquifer of the Mexico's Valley in recent years. The Cutzamala system was composed of three stages of construction, and they were originally designed to export into the Valley of Mexico a maximum flow rate of 19 m^3/s (599 hm^3/year), however, the system has stabilized itself at 16 m^3/s (505 hm^3/year).

Valle de Bravo Dam

Valle de Bravo dam covers a surface of 2900 hectare and it has an altitude of 1768 meters above sea level. The maximum storage capacity was initially 457 hm^3, reduced by blockage to 394.66 hm^3. Nevertheless, the artificial lake was the promoter of the tourist activity and currently must keep a certain minimum level due to socio-economic activities seated around the reservoir [10]. The average extraction is 6.8 m^3/s, which represents approximately 43 % of the total of the three dams. Typically, the highest levels of storage are reached in September, as a result of the accumulation of the runoff and they were kept until the month of March, when begin the decreases, reaching levels of minimum storage in the month of June. [10]

Villa Victoria Dam

Villa Victoria dam is located at an altitude of 2544 meters above sea level; it has a total capacity of 254 hm^3 and a useful storage capacity of 185.73 hm^3. The dam provides 18 % of the drinking water for the MCMA. Its main contribution is La Compañia River, in addition to other runoff of minor importance. Its storage is reduced during the period from April to August, and then it grows as a result of the runoff accumulation. [10]

El Bosque Dam

El Bosque dam is located at an altitude of 1741 meters above sea level; it has a total capacity of 248 hm^3 and a useful storage capacity of 202.4 hm^3. The maximum depth of the dam is approximately 40 m, with a width of 4 km and a length 6 km. The main uses are the agricultural irrigation in the neighbouring towns to the south, drinking water supply and electricity generation. Zitácuaro River or San Juan Viejo, San Isidro River and part of the Tuxpan River through tunnels and channels, as well as runoff and intermittent streams [6], supplies it. It was determined that the contribution of this dam is 6.2 m^3/s on average, which represents 39 % of the system.

3. Methodology

An historical review of the operation of the dams El Bosque, Valle de Bravo and Villa Victoria in a period from 1994 to 2011 was carried out. The system operation was accomplished with the continuity equation [13], in case of a three parallel dam system (the analysis was made by separate basins) is the following:

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

Where: i is the time interval considered (in this case months), j is the subscript corresponding to each dam, $S_{j,\,i+1}$ is the volume of final storage, $S_{j,i}$ is the volume of initial storage, $I_{j,i}$ are the inputs to the reservoir and O_j the total output obtained by the following equation:

$$O_i = Evni + Vei \quad (2)$$

Where *Evni* is the net evaporation obtained from 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 2 and the extractions percentages for each dam. In this study a monthly extraction percentage for each dam was considered equal to 1/12.
The Z curve shows the range of values of extraction and storage depending on the characteristics of each reservoir.
Thus the slope formed between the minimum points and maximum meet a range of optimal, i.e. values, at operation under these conditions is simulated, all values of extraction and storage below the slope ensure optimal operation in the system.

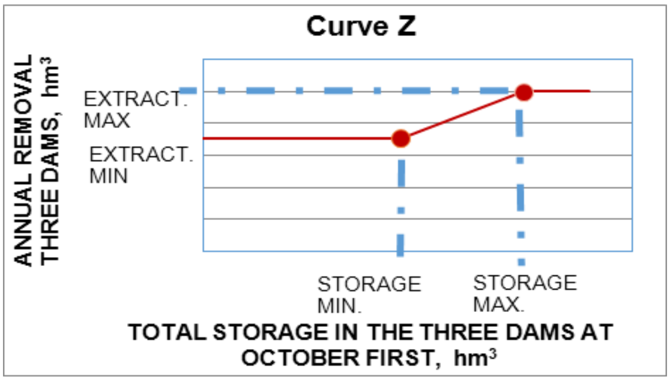

Fig. 2. Curve Z

3.1 Input data

The inflow volume for each dam recorded from 1994 to 2011 was considered for the simulation of the system operation. Figure 3 shows the inflow volumes of El Bosque dam, (similar results were determined for the other two dams, Valle de Bravo and Villa Victoria).

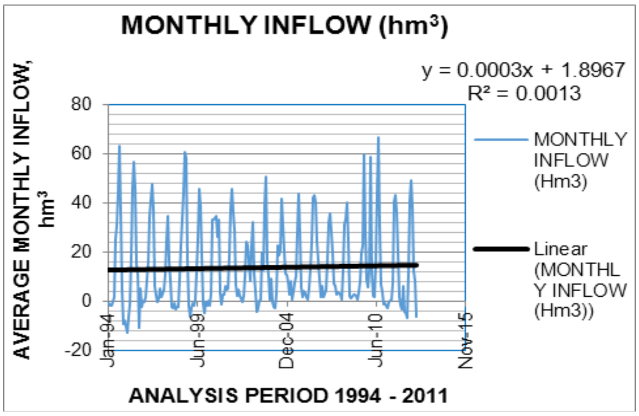

Fig. 3. Inflow El Bosque dam

The elevation was set as a function of the storage volume, as shown in Figure 4 that represents the values of the El Bosque dam; in the same way the expressions of the other two dams were obtained.

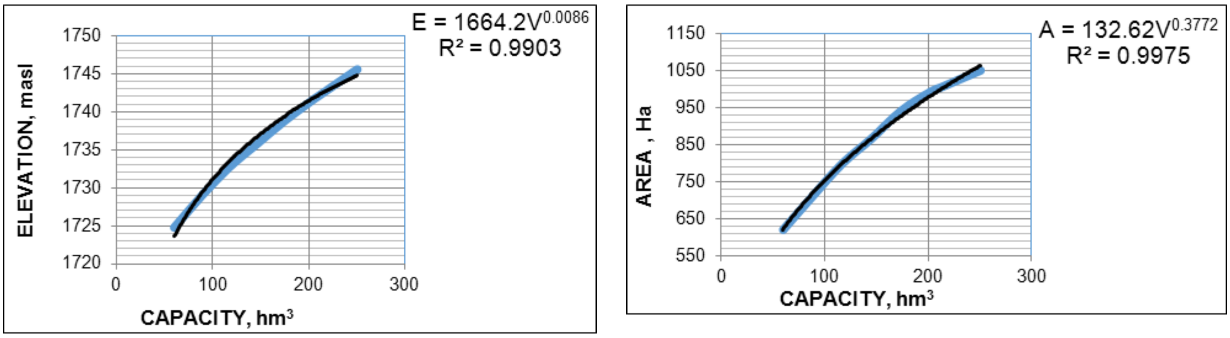

Fig. 4. Curve Elevation – Capacity – Area

In this way the analysis of the total extractions was then carried out, they were obtained from the annual historical percentages from the period 1994 to 2011 and with them the curve Z of historic extractions was built as the basis for the study of optimization. Table 2 shows the values that define the curve Z of Figure 5.

TABLE 2: Values of Total Storage and extraction curve Z for historical data

Total Storage 3 dams (hm^3)	Total Annual Extract. (hm^3)
0.00	352.65
459.80	352.65
747.20	500.00
900.00	500.00

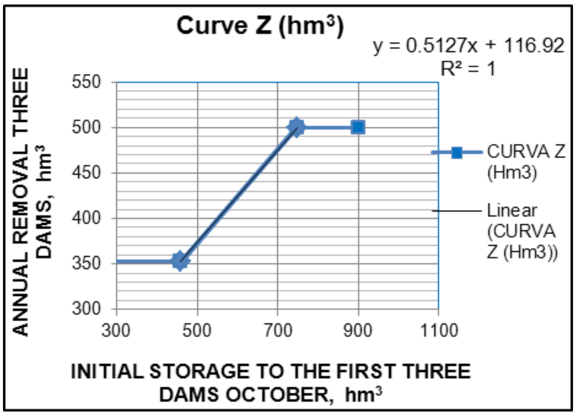

Fig. 5. Curve Z. Historical analysis

Table 3 shows the percentages of the historical total extraction for each dam.
The results of the operation for the three dams with the assumption of constant monthly extraction are shown in Table 4.

TABLE 3: Historical percentage of extraction

Dam	% ANNUAL
Villa Victoria	0.1825
Valle de Bravo	0.4265
El Bosque	0.3910
Total Annual	**1.0000**

TABLE 4: Historical operation (3 dams)

Concept	(hm^3)
Total extraction	8 011.11
Total spill	541.42
Total deficit	195.05

Based on the information obtained in the historical review, we proposed getting policies which allow obtaining the optimum extraction for the three dams of the system; helped with genetic algorithms and the simulation of the system operation.

3.2 Genetic Algorithm

Genetic algorithms had been used for optimization purposes since the middle of the eighties of the twentieth century, recent applications in hydrology and hydraulic stresses in the work of Huang [13], Zhang [14], Dominguez [15], among others.

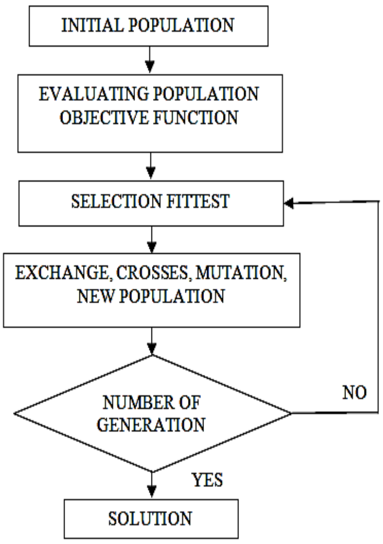

Fig. 6. Block diagram of an AG

Genetic Algorithms (GA) are adaptive methods, commonly used in problems of searching and optimization of parameters, based on sexual reproduction and on the principle of survival of the fittest." [16]. The fundamental characteristic of the GA is the use of an operator of recombination or crossing, as the primary mechanism of search, and a rendering algorithm by proportional to the performance, it is represented in a general way that the operators used on its application are the selection, the exchange or crosses and mutation, the structure of a simple genetic algorithm is presented in Figure 6 [17]. The selection can be done by the method of the roulette wheel or the stochastic universal or tournament [18]. The exchange is made at the level of binary code but can also be done at the level of real numbers; the mutation may or may not be considered and it allows new individuals appear in a generation.

In the present study, individuals correspond to sets of four parameters that make up the points on the curve of annual water extractions of the system of dams analyzed (call curve Z) the curve shows the total annual extractions as a function of the total storage for the three dams measured on October the first, tests with several parameters were carried out to analyze the behavior of the system. In a first analysis, three trials were performed where the fixed annual percentage of extraction a priori on the basis of the historic operation for each dam, leaving as variables the four points of the curve Z. In the trials 1 to 3, the objective function (OF) was to maximize the extractions by imposing penalties in case of spill and deficit conditions in the system, this is:

$$OF = Max\left\{c_e * V_e \quad - c_{der}V_{derr} \quad - c_{def}V_{def}\right\}... \tag{3}$$

Where, for the simulation period of n years, V_e is the total storage of extractions for three dams, V_{derr} is the total storage of spills for the three dams, V_{def} is the total storage of deficits for the three dams; C_e is a heavy coefficient for the extraction, C_{der} is a penalty coefficient in spill case, C_{def} is a penalty coefficient for deficit event.

In a second analysis we also considered in addition to these parameters, the percentages of annual extraction that must be assigned to each dam, i.e., the algorithm requires that the sum of the percentages of extraction be equal to 100 % of the entire system. Therefore these four tests will have 7 unknowns (3 more variables considering the extraction percentage assigned to each of the three dams). The aim of this problem is to optimize the extractions for each dam decreasing the spills and avoiding deficits that may present and identify which is the annual extraction percentage that accomplish the above assertions. Due to the fact that in trials 4 to 7 the extraction percentages of each dam were left free, we add to the OF the restriction that the sum of the percentages of annual extractions of the three dams should be 1, for this the difference was penalized respect to one of the sum of the percentages of annual extraction, and thus the equation for the OF in the following way:

$$OF = Max\left\{c_e * V_e \quad - c_{der}V_{derr} \quad - c_{def}V_{def} \quad - c_{err}Err\right\}... \tag{4}$$

Where $Err = 1 - (\sum_{i=1}^{3} pi)$; *pi* is the annual percentage assigned to the dam *i*, *i=1, 2, 3*; C_{err} is a penalty factor to minimize the value of *Err*. The program for the simulation of the system was coded in Fortran and the executable program is called by the genetic algorithm to evaluate the objective function with each individual in each generation [19]. To perform the tests with the genetic algorithm is taken into account 200 individuals and 500 generations.

TABLE 5: Parameters of lower bounds

hm^3	Lower Limit (hm^3)			
	Initial Storage Vol.	**Initial Extract.**	**Final Storage Vol.**	**Final Extract.**
Test 1	100	100	400	200
Test 2 to 7	100	250	400	350

TABLE 6: Parameters of upper bounds

hm^3	Upper Limit (hm^3)			
	Initial Storage Vol.	Initial Extract.	Final Storage Vol.	Final Extract.
Test 1	459.8	352.7	747.2	500
Test 2 to 7	459.8	352.7	747.2	500

The penalty coefficients help the genetic algorithm to find the optimal values that comply with the assertions of such equation. These penalty coefficients are shown in Tables 7 and 8.

TABLE 7: Penalty Coefficients first analysis

	Test 1	Test 2	Test 3
C_e (extract)	1	1	1
C_{derr}	10	10	100
C_{def}	1 000	1 000	1 000

TABLE 8: Penalty Coefficients second analysis

	Test 4	Test 5	Test 6	Test 7
C_e (extract)	1	1	1	1
C_{derr}	100	100	100	1 000
C_{def}	1 000	1 000	1 000	1 000
C_{err}	1 000	10 000	100 000	100 000

The test was processed by trial and depending on the results for each parameter, such as the penalty coefficients or the upper and lower limits to adjust the curve Z, in order to cover the largest values depending extraction-modified storage. [20]

4. Results and discussion

Once historical percentages of each extraction were determined, they are simulated using various genetic algorithms operating policies, for this study, seven tests that meet the requirements of water extraction were performed. Table 9 shows the results obtained and Figure 7 shows the Curve Z feature of each test.

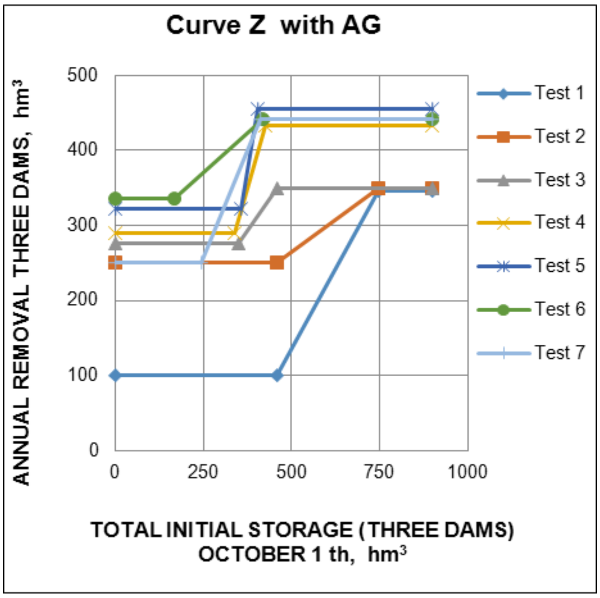

Fig. 7. Curve Z. Calculated in 7 trials

Table 9 shows that the objective function of equation 1, for the tests 1 to 3 the extraction, is below the historical (8 011.11 hm^3), although it is clear that increases with each test. However for the trials 4 and 5, the extractions are the best, but the goal is to accomplish an extraction rate of 1.

TABLE 9: Total result of the system for the seven trials

hm^3	Three Dam Total		
	Extraction (hm^3)	Spill (hm^3)	Deficit (hm^3)
Test 1	6 135.20	2 009.37	0.00
Test 2	6 238.09	1 919.46	8.68
Test 3	6 300.22	1 862.54	12.89
Test 4	8 075.30	478.31	51.55
Test 5	8 518.30	398.60	366.56
Test 6	7 399.80	924.40	0.00
Test 7	7 597.80	759.71	0.00

Tables 10 and 11 show the extraction percentages of the 7 tests, it is appreciate that the values of the tests 6 and 7 are close to 1, in fact, until the moment the Test 6 is the best option; with the intention to adjust as much as possible to the unit, two other tests were realized increasing the penalty coefficients.

TABLE 10: Extraction percentage, first analysis

Dams	Test 1	Test 2	Test 3
%P1 (EB)	0.39	0.39	0.39
%P2 (VB)	0.43	0.43	0.43
%P3 (VV)	0.18	0.18	0.18

TABLE 11: Extraction percentage, second analysis

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**

It is then analyzed which was the maximum historical total storage of October the first and this was 782.52 hm^3, this value is found in the year 1994, when it was assumed that reservoirs were at NAMO, this means that the three dams were at their highest levels. Therefore there were a couple of trials where values are adjusted to the Final Storage Volume in the lower and upper limits, see tables 12 and 13. In addition to modify the penalties; ensuring minor spills and deficits in this new essay, see Table 14.

TABLE 12: New parameters lower limits

hm^3	Lower Limit (hm^3)			
	Initial Storage Vol.	Initial Extract.	Final Storage Vol	Final Extract
Test 8	100	250	**783**	350
Test 9	100	250	**783**	350

TABLE 13: New parameters upper limits

hm^3	Lower Limit (hm^3)			
	Initial Storage Vol.	Initial Extract.	Final Storage Vol	Final Extract
Test 8	100	250	**783**	350
Test 9	100	250	**783**	350

TABLE 14: New penalty coefficients

	Test 8	Test 9
C_r (extract)	1	1
C_{derr}	10 000	100
C_{def}	1 000	1 000
C_{err}	100 000	100 000

Values that can be found with these new parameters are shown in the Table 15, where the results found are the best compared with the historical and they have the best behavior; in the percentages that correspond to each dam was found overexploitation of 27 % for the Test 8 as shown in Table 16, therefore for the test 9 is adjusted this extraction percentage almost the value of 1 using the best coefficients discussed above.

TABLE 15: Total Result last two trials

hm^3	Total		
	Extraction (hm^3)	**Spill (hm^3)**	**Deficit (hm^3)**
Test 8	8 219.90	421.91	94.86
Test 9	8 219.90	421.91	94.86

TABLE 16: Extraction percentages improvement

Dams	Test 8	Test 9
%P1 (EB)	0.43	0.35
%P2 (VB)	0.61	0.44
%P3 (VV)	0.24	0.21
SUM	**1.2772**	**1.0011**

The graph in Figure 8, shows the curve Z from these two trials, it is worth to mention that the Test 9 will be considered as optimal.

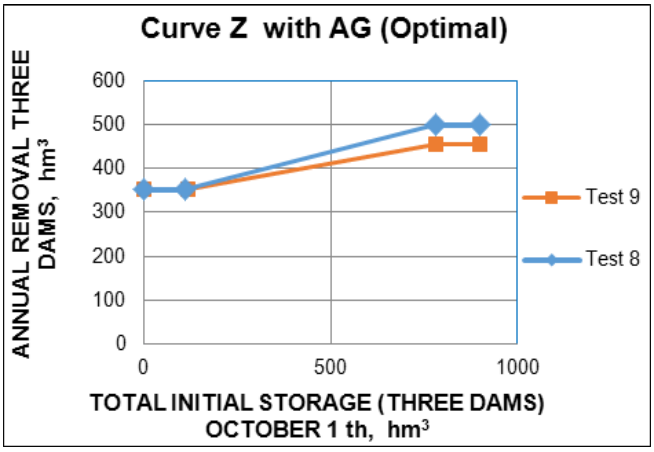

Fig. 8. Curve Z with the last two trials

Therefore, the extraction percentage associated with each dams in the Cutzamala System is shown in Table 17 and compared with the historical values for its best analysis:

TABLE 17: Comparative extraction percentages of each dam

Dams	Historical	Test 9
%P1 (EB)	0.39	0.35
%P2 (VB)	0.43	0.44
%P3 (VV)	0.18	0.21
SUM	1.0000	**1.0011**

TABLE 18: Total Historical Comparative against Test 9

	Historical (hm^3)	Test 9 (hm^3)	(%)
Total Extraction	8 011.11	8 219.90	102.61 %
Total Spill	541.42	421.91	77.93 %
Total Deficit	195.05	94.86	48.63 %

In the table above it can be concluded that El Bosque dam reduces the extraction in an 11.19 %; in Valle de Bravo dam is increased by a 3.43 % and, for the Villa Victoria dam also increases the extraction in a 16.54 % compared with what is currently being done in the system.
Table 18 gives a comparison of the total the historic operation against the total test 9 to analyze in which proportion the situation was improve in the Cutzamala System.
Finally, Figure 9 shows a graphical comparison of the extracting behavior of El Bosque dam with simulation of Test 9 against the historical one.

Should be remembered that the historical data are in Tables 2, 3 and 4 where it shows the curve Z, extraction percentages and the historical operation, respectively; Operating results of analysis with measured data.

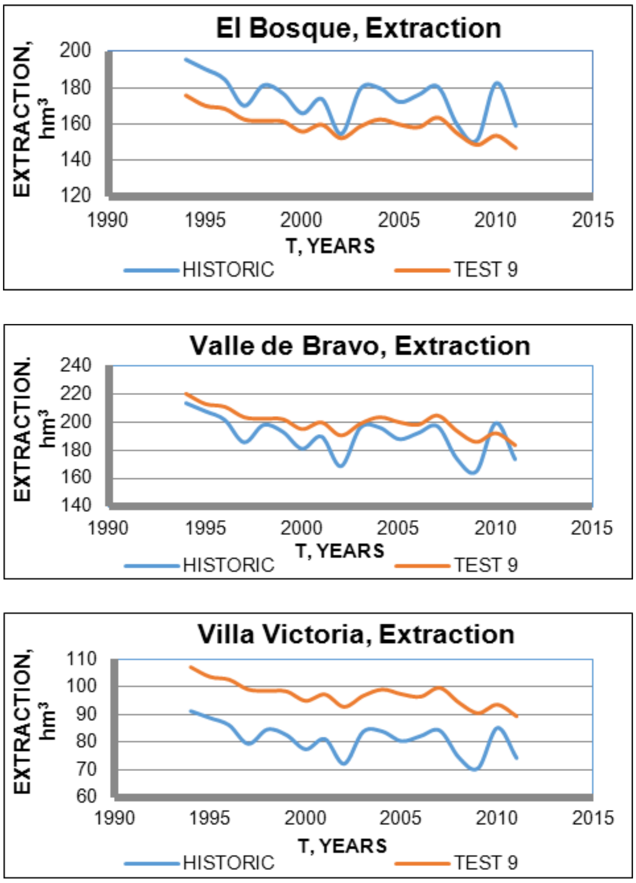

Fig. 9. Extraction. El Bosque, Valle de Bravo and Villa Victoria Dam

We must remember that with the historical review of the operation, with a period of 17 years, total withdraws of 8 011.11 million m^3 were found in the system, total spills of 541.42 million m^3 and a total deficit of 195.05 million m^3, if we have used the extraction policy 9, it would have been a more appropriate operation, with its extraction is slightly higher (8 219.90 million m^3) spills decline (421.91 million m^3) and the deficit is reduced almost half (94.86 million m^3). In this way the values that form the optimal curve Z are shown in the Table 19 and plotted in Figure 10.

TABLE 19: Optimal values Curve Z

Test 9	
Storage (hm^3)	**Extraction (hm^3)**
0.00	351.61
117.71	351.61
782.77	456.22
900.00	456.22

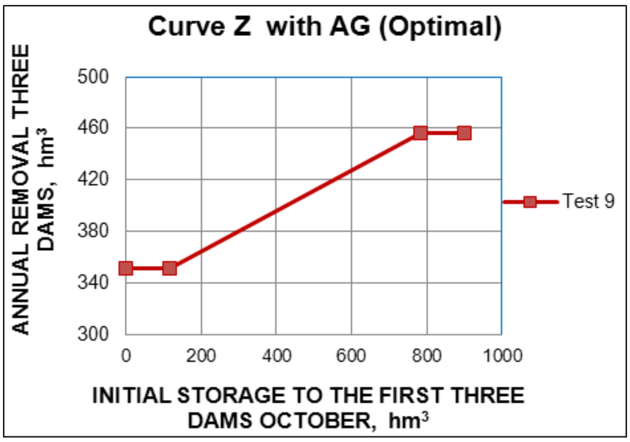

Fig. 10. Curve Z with optimal values (Test 9)

5. Conclusions

The Cutzamala System is the most important work of hydraulic infrastructure in the central region of Mexico; its main objective is to supply at least 16 m^3/s of water to the capital of the country since 1982. The system is formed by Tuxpan and El Bosque dams, located in the state of Michoacan, as well as the Ixtapan del Oro, Villa Victoria, Valle de Bravo, Chilesdo and Colorines, in the State of Mexico; each one is part of the system of Cutzamala River.
In this study were obtained annual operation policies to know the increasing demand of drinking water using three of the most important dams of the system: El Bosque, Valle de Bravo and Villa Victoria, assuming that it operates as a parallel system, this is because the information about diversion dams is not known . One hypothesis considered in the operation of the reservoirs was to assume a constant monthly extraction at each year for the three dams. Used Evolutionary Algorithms, in particular genetic algorithms, to evaluate an objective function in which it seeks to maximize the extractions and minimize, imposing penalties, the presence of spills and deficit in the main dams of the system. The operation of the assembly with the rules of operation, as well as defined was simulated using the historical record of income volumes in the year 1994 to 2011. The optimal policy found succeeded in reconciling the objectives successfully.
Once analyzed the historical data on the basis of a operation of reservoirs found the total extraction of the system that was 8 011.11 million m^3, with total spill of 541.42 million m^3 and a total deficit of 195.05 million m^3, that compared with the result of the Test 9 provides that the total annual extraction of a year (it is considered a year for the total of the system, the storage accumulated in the first October), met with a most appropriate extraction, which is greater with 8 219.90 million m^3, spills diminish significantly to 421.91 million m^3, while the deficit is reduced almost to the half with 94.86 million m^3.
In this way it is determined that the dam El Bosque must be extract a 35 % of the total annual extraction, to Valle de Bravo a 44 % and Villa Victoria must comply with 21 %. While it is a policy that the extraction is greater in a 2.61 % compared with the total extraction historic, met the objective of obtaining the lowest possible spill and same with the deficit, which is able to almost half to the three dams Cutzamala System.
The results obtained here assume the three dams analyzed work in parallel, in other words, they are independent and supply to the water treatment plant water Los Berros, this is a hypothetical case due to the fact that actually the Tuxpan dam connects with El Bosque that in turn overflowed to Valle de Bravo along with the of Ixtapan del Oro and Colorines diversion dams, while Villa Victoria and Chilesdo if fed directly to the water treatment plant.

References

[1] International Commission on Large Dams IGBC / ICOLD, "Dams and water in the world. A book about the role of dams in water management", Spain, Madrid;
[2] G. Popov, A. Krasteva, B. Kostov, D. Ivanova, Kl. Klimentov, "Optimization of the energy consumption of a pump system used for industrial water supply", Annals of faculty engineering Hunedoara – international journal of engineering, Tome XII ISSN: 1584-2665, Romania, 2014;
[3] J. Legorreta, MC. Contreras, MA. Flores, N. Jimenez, "External Basins", Ecologica - Water. Manualplaneta.com, Exploring Ecotourism, 1997;
[4] C. Tortajada, E. Castelán, "Water Management for a Megacity: Mexico City Metropolitan Area", Article AMBIO: A Journal of the Human Environment, 32 (2):124-129. 2003;
[5] INE, National Institute of Ecology, "Prioritization and recommendations for conservation actions in the Cutzamala basins System", Address of Integrated Watershed Management", Directorate general for research of ecological management and conservation of ecosystems with water, 2009;
[6] White Book, "Sustainability of the System Cutzamala", National Water Commission, pp. 93-95, 2012;
[7] O. Escolero, S. Martinez, S. Kralisch, M. Perevochtchikova, "Vulnerability of the sources of drinking water supply for the City of Mexico in the context of climate change", Mexico City, Center of Atmospheric Science, UNAM, 2009;
[8] C. Cristescu, C. Dumitrescu, G. Vrânceanu, L. Dumitrescu, "Considerations on Energy Losses in Hydraulic Drive Systems", "Hidraulica" (No. 1/2016) Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics, ISSN 1453 – 7303, pp. 36-46, 2016;

[9] C. Tortajada, "Environmental Sustainability of Water Management in Mexico", Third World Center for Water Management, Mexico, 155 p., 1999;
[10] CNA-SEMARNAT, "Cutzamala System. Water for millions of Mexicans", Working paper of the Regional Management of waters of the Valley of Mexico and Cutzamala System, Mexico, pp. 3-31, 2005;
[11] V. Bunge, J. Martinez, K. Ruiz-Bedolla, "Scenarios of the hydric dynamics in the region of input from the Cutzamala system", Working Document of the Directorate General for ecological management and conservation of ecosystems, National Institute of Ecology and Climate Change, Mexico, 2012;
[12] F. Aparicio, "The fundamentals of surface hydrology", Mexico, 1992;
[13] Wen-Cheng Huang, Lun-Chin Yuan, Chi-Ming Lee, "Linking genetic algorithms with stochastic dynamic programming to the long-term operation of a multireservoir system Water Resources Research", 38, pp. 401-409, 2002;
[14] X. Zhang, R . Srinivasan, D. Bosch, "Calibration and uncertainty analysis of the SWAT model using Genetic Algorithms and Bayesian Model Averaging", Journal of Hydrology, Volume 374, issues 3-4, pp. 307-317, 2009;
[15] M. R. Dominguez, J. M. L. Arganis, "Validation of methods to estimate design discharge flow rates for dam spillways with large regulating capacity", Hydrological Sciences Journal 57 (3), pp. 460-478, 2012;
[16] M. Gestal, D. Rivero, J.R. Rabuñal, A. Pazos, "Introduction to genetic algorithms and genetic programming", La Coruña, pp. 11-18, 2010;
[17] J. Holland, Adaptation in Natural and artificial systems, MIT Press, 1975;
[18] D. E. Goldberg, "Genetic algorithms in search, optimization and machine learning", Boston, MA. Addison-Wesley, 1989;
[19] R. Mendoza, "Program Manual: SIMEPPAR.FOR", Morelia, Mich., Institute of Engineering, UNAM, 2013;
[20] MATLAB Reference Guide. The MathWorks, Inc., 1992.