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Articles

Obtaining optimal operation rules by means of evolutionary computation and GRG algorithms: Cointzio Dam, Michoacán, Mexico

Políticas de operación óptima por medio de cómputo evolutivo y algoritmo gradiente reducido generalizado: Presa Cointzio, Michoacán, México

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Abstract

In this study, operating policies of the Z curves type were obtained, using two optimization methods: the Generalized Reduced Gradient (GRG)

Nonlinear and a simple Genetic Algorithm (GA), and they were applied to a reservoir located in the Cuitzeo lake basin, which plays an important role in supplying water to a part of the population of the city of Morelia and in the irrigation of several modules of the Irrigation District (DR) 020, known as Morelia-Queréndaro. With each policy obtained, the operation of the system was simulated, using the historical record of inflow volumes into the system, to compare with the reported by the National Water Commission (Conagua) and those that maintained the balance between compliance with demands and less presence of spills or deficits. Finally, to review the behavior of the system in the long term when using the selected policies, series of synthetic monthly inflow volumes with 100 years of record were simulated, generated with the Svanidze method. The comparison of the deficit and spillage results at the monthly and annual level of the simulations carried out with the historical Z curve, GA and GRG, indicated that the GA had an acceptable behavior both in the historical period and in the long term, since, although the volumes spilled increased, the magnitude in which they did so is less than the magnitude in which the deficit was reduced and as the Cointzio dam has been used to supply water to the Vista Bella water treatment plant and for irrigation of 4 of the 5 modules of the irrigation district 020, the operating rule that best controlled the deficit event was chosen.

Keywords: Operation rules, reservoir operation, genetic algorithm, generalized reduced gradient, irrigation and drinking water, Cointzio dam.

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Resumen

En este estudio se obtuvieron políticas de operación del tipo curvas Z, usando dos métodos de optimización: el de gradiente reducido generalizado (GRG) no lineal y un algoritmo genético (AG) simple, y se aplicaron a un sistema de aprovechamiento hidráulico localizado en la cuenca del lago de Cuitzeo, que juega un papel importante en el abastecimiento de agua a una parte de la población de la ciudad de Morelia y en el riego de varios módulos del Distrito de Riego (DR) 020, conocido como Morelia-Queréndaro. Con cada política obtenida se simuló el funcionamiento del sistema, usando el registro histórico de volúmenes de ingreso al sistema, para poder comparar con lo reportado por la Comisión Nacional del Agua (Conagua), y se eligieron aquellas que mantuvieron el balance entre cumplimiento de demandas y menor presencia de derrames o de déficits. Finalmente, con el fin de revisar el comportamiento del sistema en el largo plazo al utilizarse las políticas seleccionadas, se simularon series de volúmenes de ingreso mensual sintéticos con 100 años de registro, generados con el método de Svanidze. La comparación de los resultados de déficit y derrames a nivel mensual y anual de las simulaciones realizadas con la curva Z histórica, AG y GRG, indicaron que el AG tuvo un comportamiento aceptable tanto en el periodo histórico como a largo plazo, pues aunque los volúmenes derramados aumentaron, la magnitud en la que lo hicieron es menor a la magnitud en la que se redujo el déficit, y como la presa de Cointzio ha sido utilizada para suministro de agua a la planta potabilizadora de Vista

Bella y para riego de 4 de los 5 módulos del Distrito de Riego 020 se eligió la regla de operación que controló mejor el evento de déficit. El algoritmo GRG reportó múltiples ventajas, entre ellas su facilidad de uso y la rapidez con la que encuentra resultados, siempre que no se indiquen demasiadas iteraciones; sin embargo, una desventaja del método es que no siempre converge a un óptimo global, ya que para distintos valores iniciales de la política Z el algoritmo dio diferentes valores óptimos. El AG, por su parte, converge a óptimos globales para cada simulación debido a que cada vez que se aplica el proceso se genera aleatoriamente una población y el resultado fue el mismo para unas condiciones de coeficientes de penalización dadas. Una limitante del método de los AG es el tiempo de cómputo empleado para la obtención de resultados.

Palabras clave: políticas de operación, funcionamiento de vaso, algoritmo genético, gradiente reducido generalizado, riego y agua potable, presa Cointzio.

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Introduction

Among the many uses of hydraulic systems, two stand: domestic and agricultural water supply (Conagua, 2007). The first because its coverage is an indicator of social welfare, and the second because this is where most extracted water, from the surface and underground sources, is used (Semarnat, 2002). In 2015 The National Water Information System (SINA) reported that 97.8 % of the population in urban areas had access to drinking water, and 87.0 % in rural areas (Conagua, 2020). Data from several federal institutions show that in Mexico the predominant use of water is agricultural; in 2000 78 % of water extracted was used to irrigate 6.3 million hectares of land (Semarnat, 2002).

However, as water is an increasingly scarce resource on the planet, the operation and management of hydraulic systems need not only previous studies into technical feasibility and environmental impacts, but also operating policies that can be consulted by management. This allows for efficient management of the resource, maintaining a balance between meeting the demand for water and avoiding spills that affect downstream populations. These operating rules must be kept up to date to face changes induced by anthropogenic activity and also in the climatological

The objective of this study is to obtain operating policies using two optimization methods: the Generalized Reduced Gradient (GRG) (López & Sánchez, 1998) and the Nonlinear and a simple Genetic Algorithm (GA)

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(Holland, 1975; Goldberg, 1989), and to apply them to a hydraulic system in the Cuitzeo lake basin, which plays an important role in supplying water to some of the population of the city of Morelia and in the irrigation of various modules of the District of Irrigation (DR) 020, known as Morelia-Queréndaro. For each policy obtained, the operation of the system is simulated, using the historical records of volumes entering the system, to compare this with that reported by the National Water Commission (Conagua). (This is the federal agency in charge of the management and operation of hydraulic systems in Mexico.) From this, a balance can be kept between meeting water demands and avoiding spill events. Finally, to review the behavior of the system in the long term when using the selected policies, a series of synthetic monthly inflow volumes, with 100 years of records were simulated, generated with the Svanidze method (Svanidze, 1980).

This work is organized into 6 more sections: in the second, a review is made of both national and international works that apply optimization techniques to obtain operating rules and that apply them to particular cases. In the third section, the study site is described. In section 4 methodologies used in this work are presented, while in the fifth the considerations made for the application of these methodologies to this particular hydraulic system are described. Finally, the conclusions of the study are given.

State of the art

In the last decades, studies have been carried out in which different algorithms are applied in search of optimal operating policies; such as Cancelliere, Ancarani, and Rossi (2002), who used both dynamic programming and neural networks to obtain operation policies for irrigation purposes, which they successfully simulated in periods of normal runoff and drought in the Pozzillo reservoir of the Salso river in Sicily. Moghaddasi, Araghinejad, and Morid (2010) used Lagrange multiplier methods to optimize decision variables in long-term operating models in the Zayandeh-rud reservoir in Iran. Wua and Chen (2014) used an optimization method of the NelderMed type, combined with an evolutionary random search algorithm, coupled with hydrological simulations to obtain flexible operating policies which reconcile the electricity generation, irrigation, and drinking water objectives, in the Xinfengjiang reservoir, China. Kumar *et al*. (2013) used fuzzy logic tools and applied them in the hydraulic system of the Sutlej River, in India. Kang and Woo (2014) used a deterministic model to forecast water flows and demands, using the global optimization method, called the complex evolution and mixing method (Shuffled Complex Evolution SCE-UA) from the University of Arizona (Gotay & Jorge, 2003). They used an objective function that seeks the optimal extraction of water in different periods to obtain new operating rules with more reasonable solutions than those of

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the past. They also developed a water demand prediction model, whose function is to maximize the energy generated by the hydroelectric plant and reach a target level in the reservoir for each period of operation. The models obtained were applied to the Balam and Seomjingang reservoirs. Ndiritu *et al*. (2016) evaluated the operating rules of the Hluhluwe dam, South Africa, improving decisions that had been based on experience, considering non-linear optimization and simulation of synthetic series, to obtain monthly water allocation curves.

Minjares, Salmón, Orozco, and Cruz (2008) used genetic algorithms in an annual hydrological-agronomic-economic model to optimize the management of the Yaqui river reservoir system and select an optimal crop pattern according to the maximum economic performance and the optimal monthly extractions of irrigation water. Malekmohammadi, Kerachian and Zahraieb (2009) applied a genetic algorithm to optimize the flood system for Iran's Dez River. Together with the law of irrigation demand, they fed a second variable chromosome genetic algorithm into data for a Bayesian network to obtain an improved optimal monthly withdrawal. Chang, Chan, and Shin (2010) used genetic algorithms restricted by ecological runoff requirements in an objective function that integrates a set of penalties for different restrictions to optimize the extractions of the Shih-Men dam, Taiwan. Falllah-Mehdipour, Bozorg and Mariño (2013) applied genetic algorithms, particle swarm optimization algorithms, and leap-frog optimization algorithms to determine the optimal multipurpose output planning for a specific time series in a linear and non-linear fashion. Acuña (2014) made a historical review of the inflow to dams of the Cutzamala System in Mexico, to generate a Z-type curve defined by the minimum storage / minimum extraction and the maximum storage / maximum extraction. They subsequently used a genetic algorithm that adjusts the 4 parameters of the curve to optimize extractions, reduce spillage and avoid any deficits.

Study site

The Cointzio dam (Figure 1) is located on the limits of the states of Michoacán de Ocampo and Guanajuato, Mexico (Cram, Galicia, & Israde, 2010). It is part of the Cuitzeo basin, in the RH-020 hydrological region "Lerma-Santiago". The basin has an area of 3,657 km^2 (Conagua & CEAC, 2009), of which 643 km^2 (17 %) correspond to the Cointzio dam sub-basin (Susperregui, Gratiot, Esteves, Duwig, & Prat, 2007).

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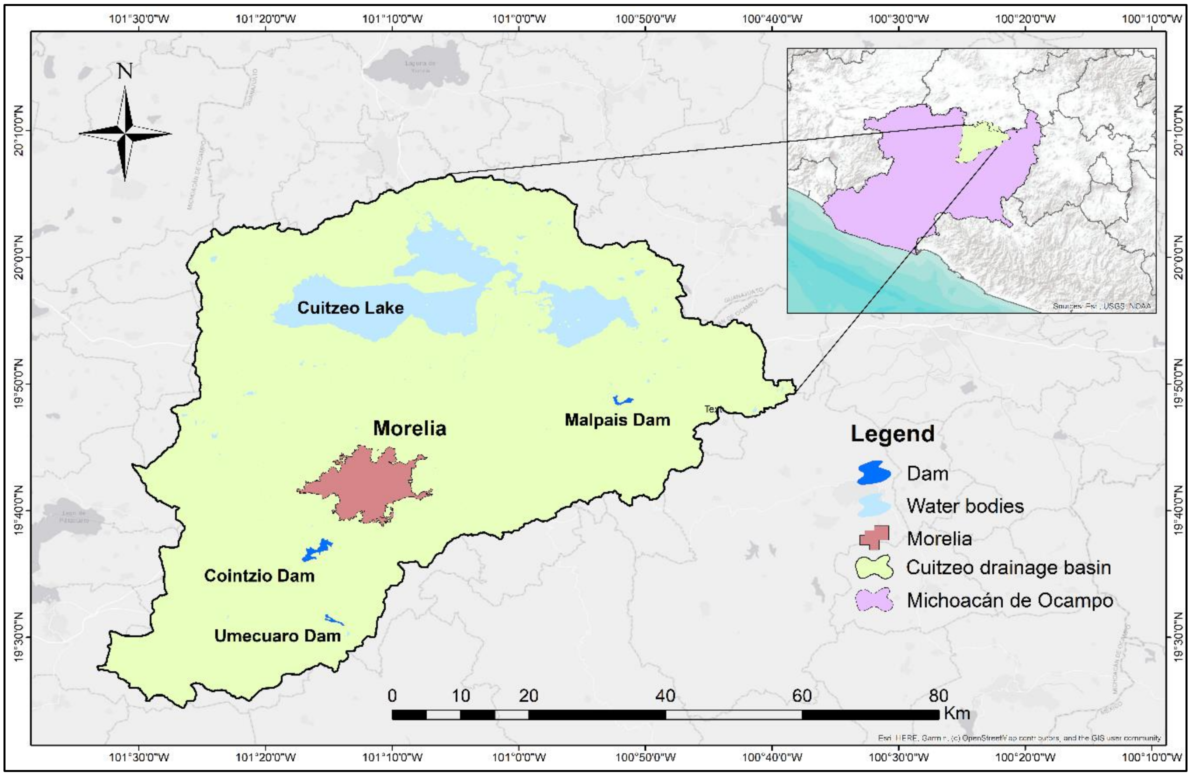

Figure 1. Location of the Cuitzeo lake basin (authors design).

The dam dates from the 1930s, when it was built to take advantage of the waters of the Tirio and Tiripetío rivers (García, 2011) and provide water to the Irrigation District, DR 020 Morelia-Queréndaro, and for hydroelectric power (until 1982). As of 1950, the reservoir also supplies drinking water to the city of Morelia, providing 23 % of the total volume of water required (OOAPAS, 2018).

The curtain of the Cointzio dam is located at the geographic coordinates: Latitude 19.6139 and Longitude: -101.166, according to the

National Bank of Surface Water Data (BANDAS) of the Mexican Institute of Water Technology (IMTA). Table 1 summarizes the areas and capacities of the reservoir for different elevations.

Table 1. Elevation-Storage-area of Cointzio dam (Conagua, 2019).

Level	**Elevation (msnm)**	**Volume (hm^3)**	**Area (ha)**
Crown	2002.82	88.57	640.21
MWL	2001.32	79.23	604.74
MOWL	1999.47	68.51	551.28
Spillway crest	1995.97	50.83	463.28
mWL	1972.31	0.90	47.48

Materials and methods

To obtain an optimal operating policy the volume of water that must be extracted to satisfy all the demands and obtain the maximum benefit

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during operation must be identified (Alegría, 2010); the volume to extract depends on the initial storage.

As this is a dam that contributes part of the volumes extracted for the irrigation of DR 020, these volumes should be maximized to obtain optimal benefit during the operation of the reservoir. Therefore, the objective function of Equation (1) is used, which maximizes the outlet extractions, at the same time as penalizing to a maximum the volumes of spills or deficits. With this equation it is possible to give greater importance to the volumes spilled, or to the volumes of deficit, depending on the coefficients that affect them:

$$FO2 = Max\left(Cr * Vol_{riego} - Cderr * Vol_{derramado} - Cdéf * Vol_{déficit}\right) \quad (1)$$

Where:

$Vol_{spilled}$: volumes spilled on the spillway (hm^3).

$Vol_{deficit}$: volumes of deficit (hm^3).

Vol_{irrig}: volumes extracted for irrigation from the intake work (hm^3).

Cr: the coefficient that affects the irrigation volume (dimensionless), set at 1 for all simulations-optimizations.

Cderr: coefficient of spill penalty (dimensionless).

Cdéf: coefficient of deficit penalty (dimensionless).

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Three combinations of the coefficients for spill and deficit penalties were defined to obtain an operating policy with each: (1 000, 500) (1 000, 1 000) and (500, 1 000).

Once the operating rule is found, it is necessary to simulate the operation of the system to evaluate the behavior in greater detail, mainly of the spill and deficit variables. For this, the continuity equation is used, in which a time interval Δt can be written as in Equation (2):

$$E - S = \Delta V \tag{2}$$

Where:

E: are the reservoir inflow volumes for the interval considered (hm^3)

S: are the reservoir outflows for the same interval (hm^3)

Δ*V*: is the variation in the volume stored (hm^3)

Figure 2 shows the flowchart of the reservoir operation at the annual level. The initial storage volume in the year, i = 0, equals the volume at NAMO (68.51 hm^3); for subsequent years, *i* + 1, the actual final volume calculated for the year immediately preceding it is used.

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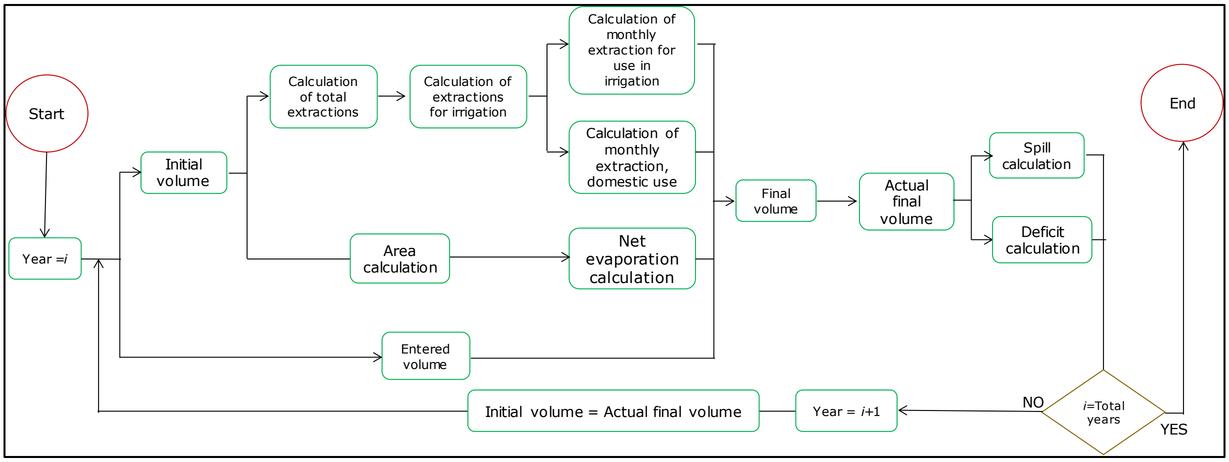

Figure 2. Flowchart of reservoir operation

The inflow volumes to the dam include the runoff for the basin, obtained from the daily operation report of the Conagua reservoir for 1940 to 2016 (Figure 3). However, negative runoff volumes can be obtained when using the continuity equation, due to lack of information or to human error in the operation report. These negative volumes are mathematically inferred but do not exist physically. Therefore, the values were corrected by substituting them with data obtained from the 12347 Santiago Undameo hydrometric station (Figure 4)

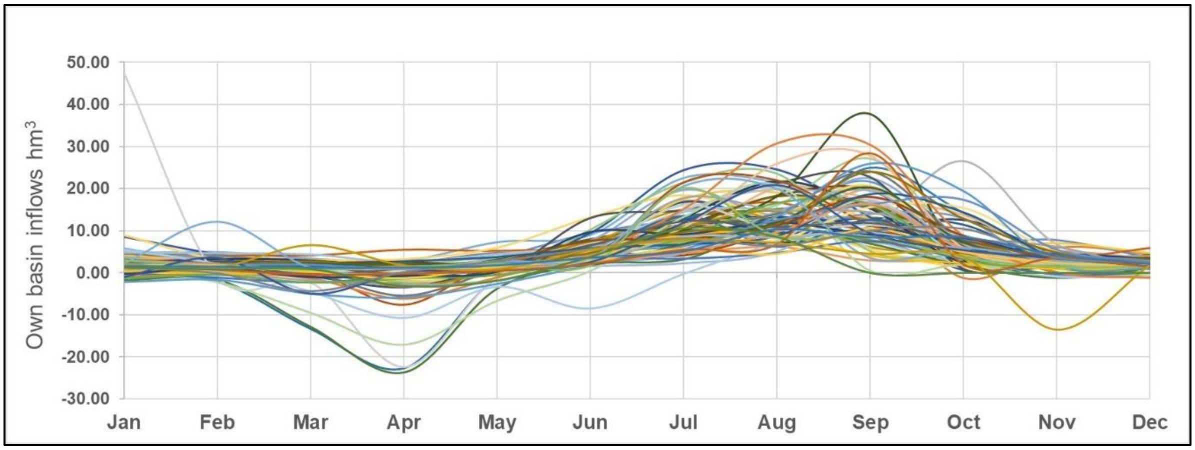

Figure 3. Deducted monthly inflows from the basin (annual series from 1940 to 2016).

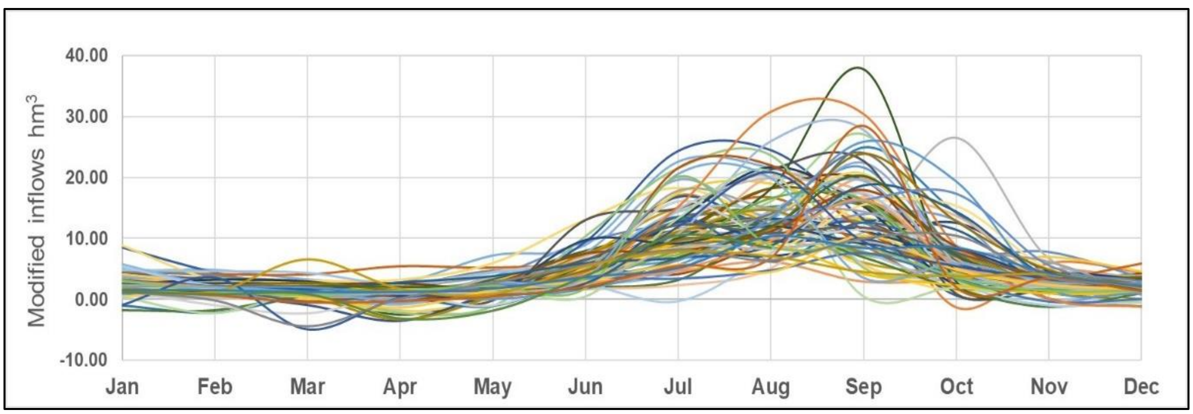

Figure 4. Corrected monthly inflows for the basin (annual series from 1940 to 2016).

For the output volumes, the volume of water extracted for irrigation and drinking water was considered, as well as net evaporation that considers the input volumes due to rain, and the outputs due to evaporation.

Optimization methods

a) The Generalized Reduced Gradient (GRG) nonlinear optimization algorithm in its GRG2 version (López & Sánchez, 1998), is the default solution method of Microsoft Excel © Solver ©. The algorithm was developed by the Leon Lasdon University of Austin (Texas) and the Allan Waren University (Cleveland) (González-Gómez, 2015). Its bases are described in Lasdon, Waren, Jain, and Ratner (1978), and Lasdon and Waren (1978).

The GRG algorithm is a process to solve equalities or inequalities subject to a set of restrictions on a set of real unknown variables, with an objective function to maximize or minimize, provided that any of the restrictions or objective functions are not linear. The method systematically searches all possible values for an optimal solution, although the algorithm can converge to a local or global optimum. Figure 5 shows the basic algorithm that Solver © follows (Caballero, 2011).

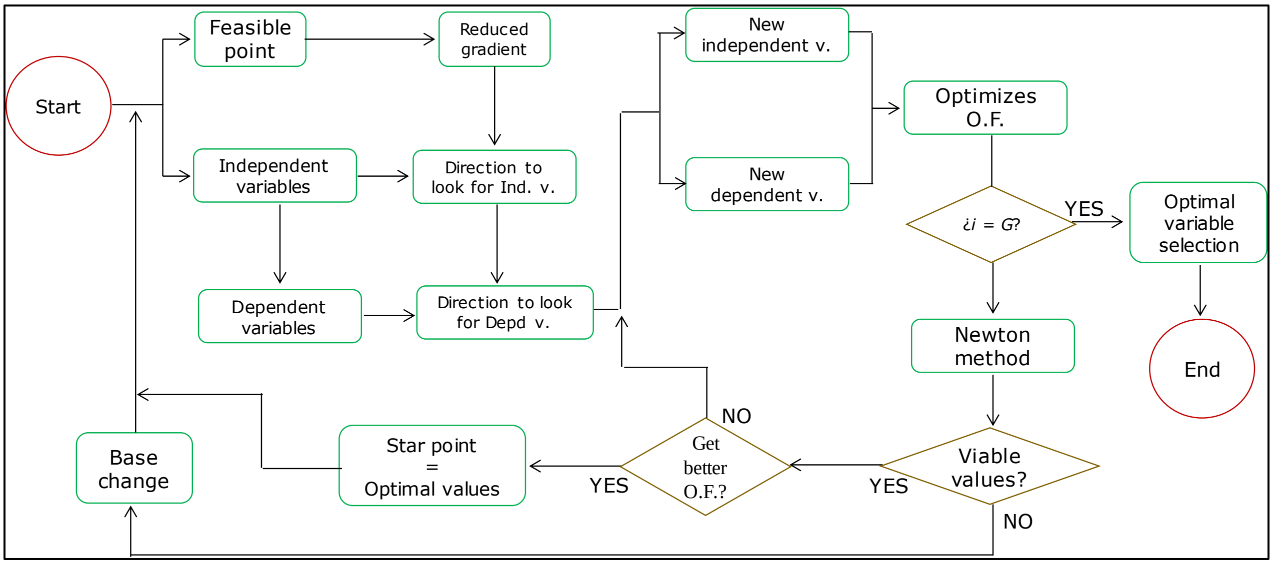

Figure 5. GRG Algorithm (Caballero, 2011).

The algorithm can be described as a movement or jump towards a direction of the feasible region, in such a way that the value of the objective function improves. The process continues until there is no feasible region to improve the objective function, or the potential for such improvement is very small.

The GRG optimization algorithm was used using a Microsoft Excel © spreadsheet, with the programmed reservoir operation. The algorithm is subject to restrictions inherent to the operation of the reservoir, while the decision cells modified the simulation by yielding new values that were evaluated in the objective function, thus deciding the next movement or jump that should be made.

b) Genetic Algorithms (GA) are based on the principle of survival of the fittest, from Darwin's theory of natural selection, so they are part of bioinspired computing and are described in detail in Goldberg (1989) and Michalewicz (1996). The advancement of technology and the increase in the speed of personal computers has made GA a very useful tool; although their application in the case of hydrology and hydraulics is more noticeable from the turn of this century. To cite a few examples: Rincón (2006); Guzmán (2009); Fuentes, Palma and Rodríguez (2011); Acuña (2014); Fuentes and Palma (2014); Arganis, Preciado and Rodríguez (2015); Pereyra, Pandolfi and Villagra (2016).

In the case of the GA, a program made in Fortran © was used that simulates the historical operation of the reservoir. The algorithm used begins with the random generation of an initial population (chromosomes) of n individuals. Each individual is formed by the coordinates that define the Z curve (genes), and input files are built with them for the program to simulate the reservoir operation; other input files are predefined. The simulation is carried out for each individual and the results are saved in output files, the values of which are evaluated using the objective function. As long as the set number of generations is not met, the algorithm randomly selects the best individuals, to which cross operators (roulette method) and gene mutation are applied to form a new generation of individuals. Crossover and mutation changes can occur at the binary level, or in the real representation, adding the mean, the standard deviation of the values , or by applying some other method (Goldberg, 1989). The new population enters the algorithm and the process is repeated until the established generations are met, at which time the best individual to optimize the objective function is selected, and with this, the solution files are built: coordinates of the Z curve and optimized monthly percentages, to make a new simulation with this optimal policy. Figure 6 shows the sequence followed to reach the optimal solution.

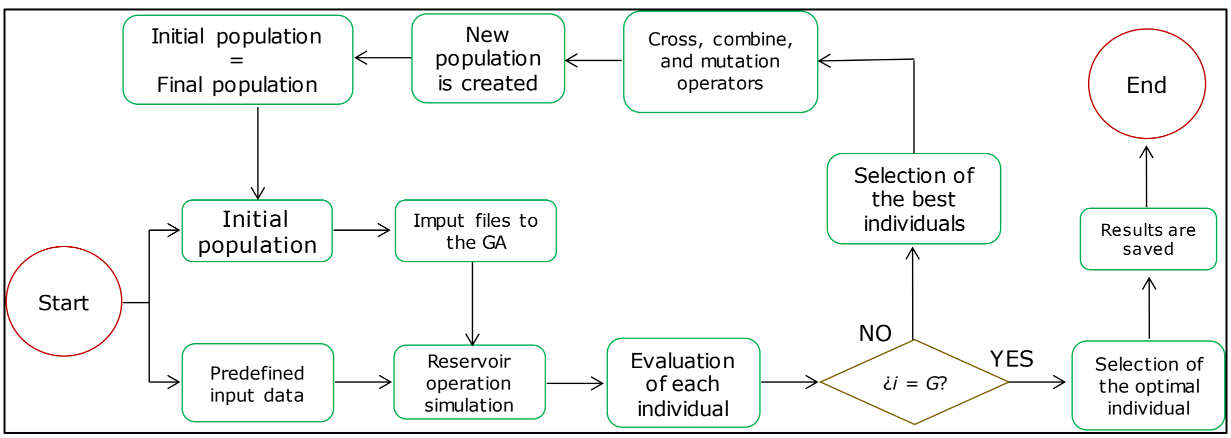

Figure 6. GA algorithm coupled with reservoir simulation.

Results

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To apply the two optimization methods, it is necessary to calculate the following, so that the reservoir operation can be simulated:

a) The monthly average net evaporation of the water surface: this was calculated as the sum of the evaporation losses and the monthly rainfall inflow, the net evaporation depths were obtained from the historical operation of the reservoir (Conagua, 2019) (Figure 7).

Figure 7. Average net evaporation depth (1940-2016).

b) The average demand for irrigation: the irrigation season in DR 020 begins in October of the year *i* and ends in June of year *i* + 1. In July, August, and September no extractions are made from the dam, which is used to store water and to prepare for the new agricultural year, taking advantage of the abundant rains of this season. Figure 8 shows the average percentage allocation of the volume destined for irrigation.

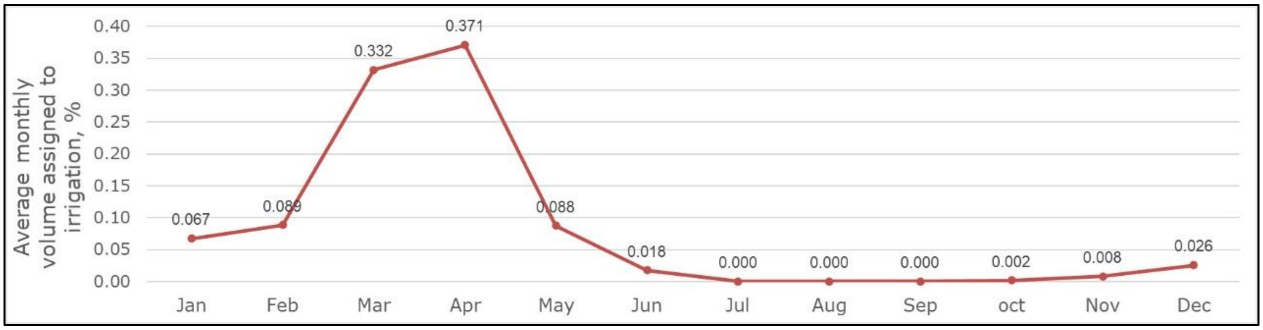

Figure 8. Percentage distribution of the volume assigned to irrigation 1998-2018 (Conagua, 2019).

c) The volume of water extracted from the reservoir to supply the water purification plant in an uninterrupted way: the distribution of domestic water depends on the Domestic Water, Sewerage and Sanitation Operator Agency (OOAPAS) of Morelia. Figure 9 shows an almost constant rate of extraction, except for February, so that the average monthly volume can be considered invariable, and equal to the average of the values (1734.27 thousand m^3/month, or 20811.2 thousand m^3/year)

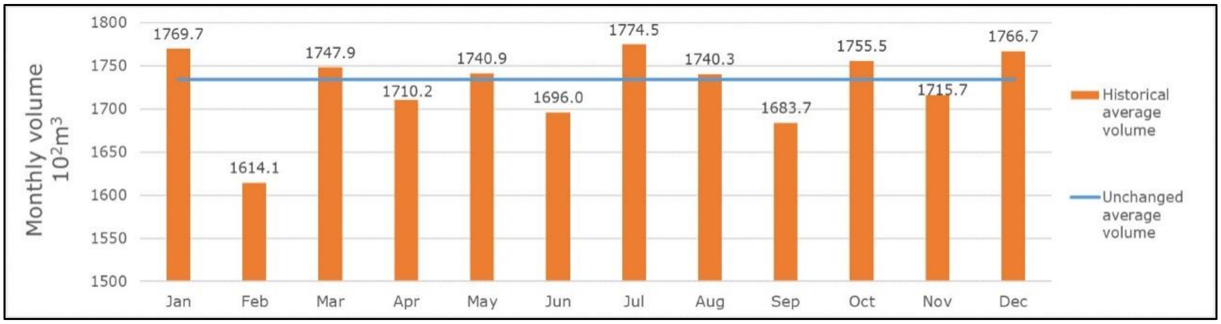

Figure 9. Average monthly volumes allocated to domestic water 1998-2018 (Conagua, 2019).

Because there was no reliable data on the elevation capacity curve from the federal agency initially, a Z curve was generated (Figure 10), from the last 5 irrigation cycles (Table 2). To determine the total extraction volumes, the sum of the volumes extracted and approved for agricultural use was used, plus the annual average volume of 20,811.2 thousand m^3 for domestic water provision. The maximum initial storage volume was equal to the capacity of the reservoir at the MOWL (see Table 1), while for the minimum initial storage the value of the storage as of October 1, 2016, was used, 54,585 hm^3. This corresponds to the minimum volume for the period 2014-2015 to 2018-2019. With this historical Z curve, a simulation was made as a reference for the monthly and annual comparisons of the results.

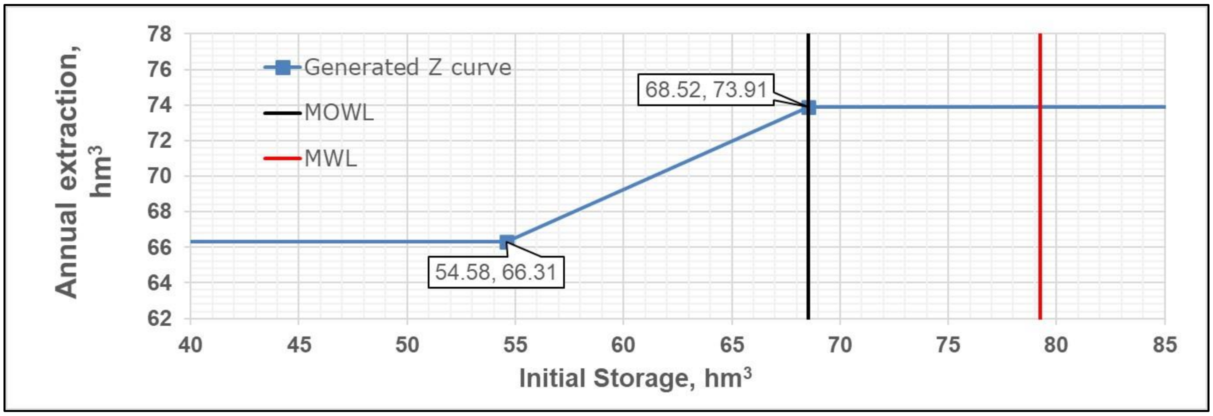

Figure 10. Z Curve: 2014-2015 to 2018-2019 (Conagua, 2019).

Table 2. Volumes approved for irrigation, 2014-2015 to 2018-2019, (Conagua, 2019).

Cycle	Irrig Vol	Domestic Water Vol	Total Vol
	hm^3	hm^3	hm^3
2014-2015	51.30	20.811	72.111
2015-2016	52.80	20.811	73.611
2016-2017	45.50	20.811	66.311
2017-2018	53.10	20.811	73.911
2018-2019	52.94	20.811	73.751

To review the long-term behavior of the system when using the selected policies, a series of synthetic monthly inflow volumes were simulated, with 100 years of records, using the Svanidze method (Svanidze, 1980). This allows periodic series to be generated, with the advantage that the data is not required to have a normal distribution (Domínguez, Fuentes, & Arganis, 2001; Arganis, Domínguez, Cisneros, & Fuentes, 2008).

This method consists of a double random procedure; first, a statistical analysis is carried out to determine the probability distribution function of best fit to the annual series, where each value is equal to the sum of the monthly inflow volumes for each basin in the hydrological year, that is, October of the year i to September of the year $i + 1$. The second procedure consists of generating synthetic fractions of the period considered (monthly), which are monthly percentages concerning the annual totals of random years. Finally, monthly synthetic data is created by multiplying the synthetic fractions of the random years by the annual volumes generated. Figure 11 shows that the total annual volumes of the historical records had the behavior of a Gumbel function with the parameters: $\alpha = 0.081$ and $\beta = 56.6254$. Different series of synthetic annual volumes were then generated using these parameters.

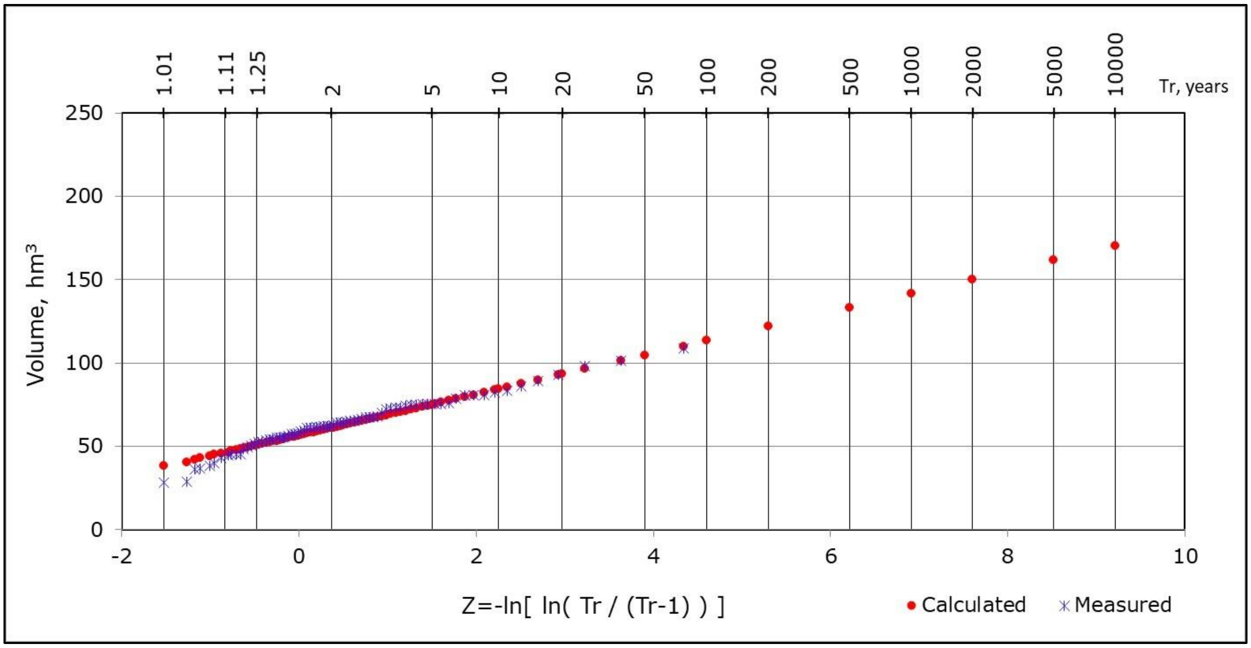

Figure 11. Total historical annual volumes and calculated Gumbel function.

Table 3 shows the average statistical values of the 10 synthetic series generated with 100 years of record each. Table 4 shows the statistical values of the historical data.

Table 3. Average statistics of the 10 synthetic series generated.

Synthetics	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Mean	6.654	2.930	2.179	2.642	1.752	1.026	0.525	2.002	5.168	11.063	13.328	14.426
Stand Dev	4.324	1.969	1.398	1.607	1.390	1.625	1.484	1.472	2.490	5.298	5.456	7.509

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Coef Skew	0.924	1.041	0.121	0.432	-0.812	-0.716	-1.214	0.027	0.968	1.024	1.655	1.107
CV	0.651	0.672	0.644	0.611	0.798	1.611	3.048	0.742	0.481	0.479	0.407	0.520

Table 4. Statistics from the historical record.

Historical	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Mean	6.621	2.876	2.169	2.628	1.789	1.067	0.627	1.950	5.114	11.139	13.442	14.324
Stand Dev	4.585	1.681	1.283	1.680	1.323	1.600	1.403	1.516	2.446	5.155	5.431	7.152
Coef Skew	1.687	0.256	-0.226	0.935	-0.536	-0.584	-0.249	0.553	1.035	0.432	0.772	0.678
CV	0.693	0.585	0.591	0.639	0.739	1.499	2.237	0.778	0.478	0.463	0.404	0.499

Figure 12, Figure 13, Figure 14, and Figure 15 show the graphical comparison of the statistics: mean, standard deviation coefficient of skewness, and the average coefficient of variation of the 10 synthetic series and the historical record, respectively.

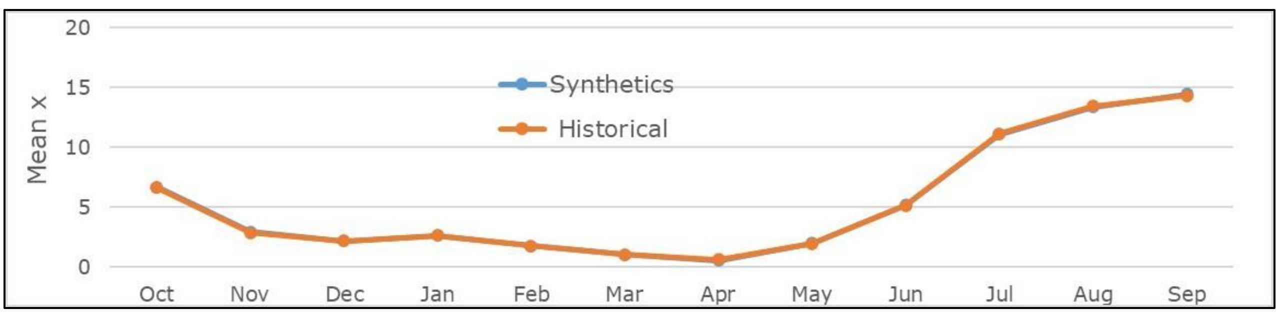

Figure 12. Mean of the historical and synthetic values

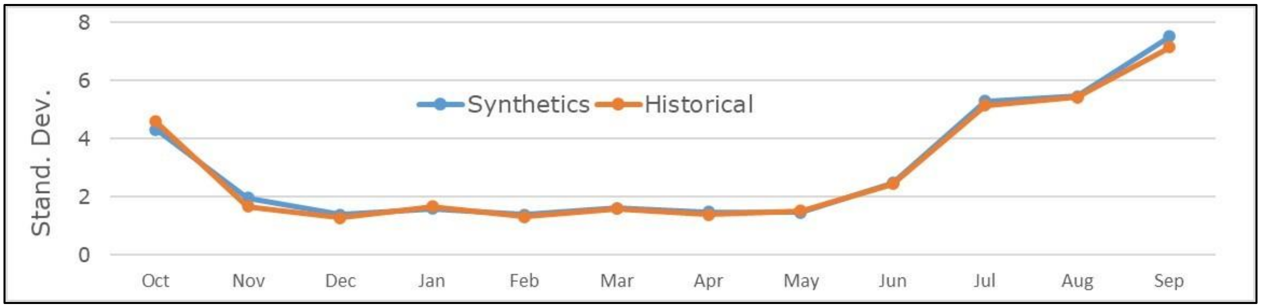

Figure 13. The standard deviation of historical and synthetic values.

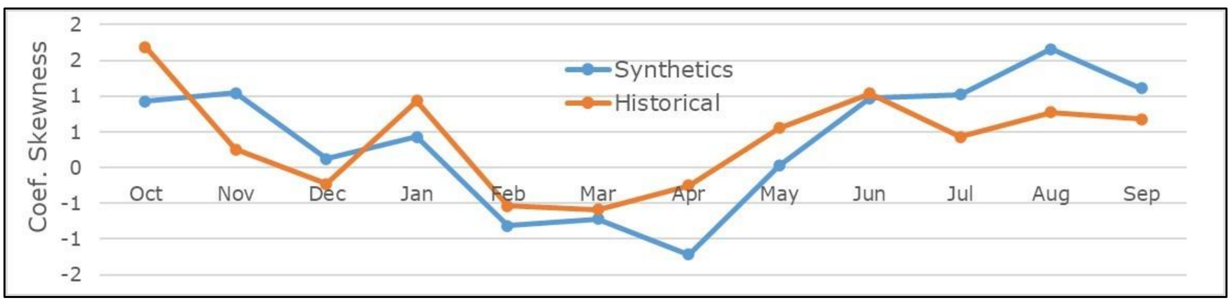

Figure 14. Coefficient of skewness of historical and synthetic values.

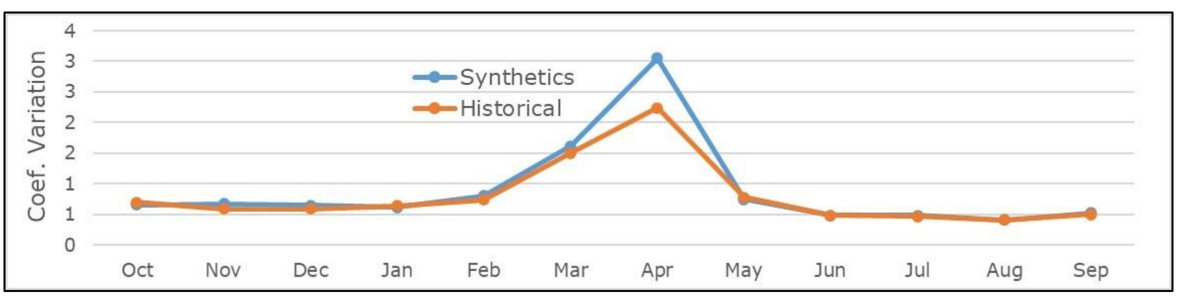

Figure 15. The average coefficient of variation of historical and synthetic values.

Table 5 shows the extracted volumes for domestic water, for irrigation, and the total volumes, as well as the spills and deficits, obtained using both optimization methods (algorithm GA and GRG Nonlinear) to optimize the objective function, setting as search variables to the coordinates of the points "a" (Minimum initial storage, Minimum extraction) and "b" (Maximum initial storage, Maximum extraction) of the Z curve.

Table 5. Result of the simulations 1940-2016.

	Irrigation Ext.	**Domestic Water Ext.**	**Spill**	**Deficit**	**cder**	**Cdef**
Simulation	**(hm^3)**					
Z	3 491.8641	1 581.6512	124.60	396.36		
GRG-B1	3 183.53	1 581.65	77.71	50.78	1 000	500
GRG-B2	3 151.49	1 581.65	89.21	33.07	1 000	1 000
GRG-B3	3 090.43	1 581.65	120.20	8.58	500	1 000
GA-1	3 385.36	1 580.8	77.83	152.61	1 000	500
GA-2	3 354.92	1 580.8	90.58	134.93	1 000	1 000
GA-3	3 310.31	1 580.8	116.41	116.06	500	1 000

In the simulation called Z, the Z curve obtained from the historical data was used (Figure 10). The GRG-B and GA simulations for the three penalty combinations used the objective function of Equation (1), taking the Z curve as the starting point (Figure 10). The simulation period was from October 1940 to September 2016.

Figure 16 and Figure 17 show the comparison between the spilled volumes and the total deficit obtained in all the simulations; the Z series corresponds to the simulation with the Z curve considered as historic.

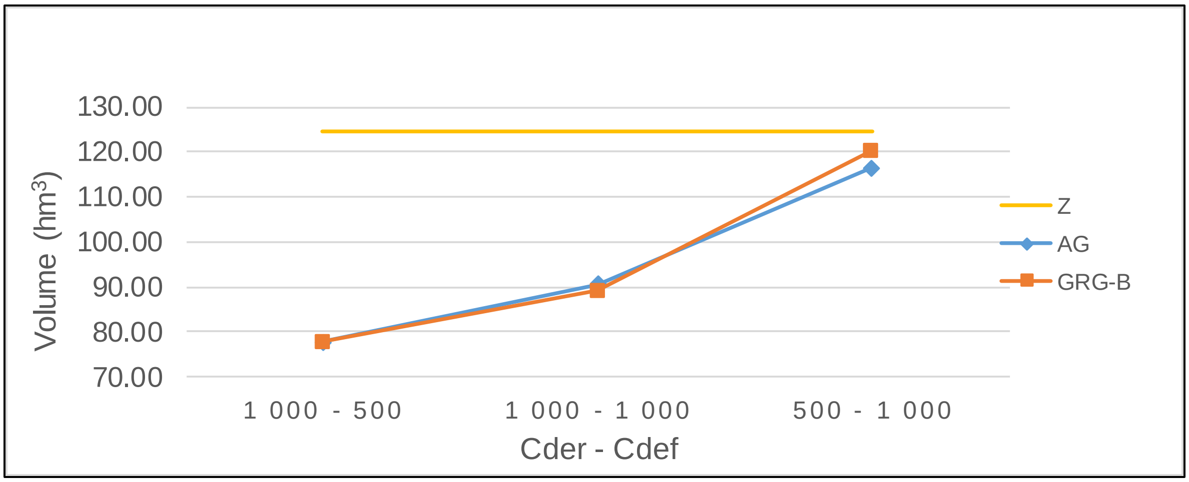

Figure 16. Comparison of total spills 1940-2016.

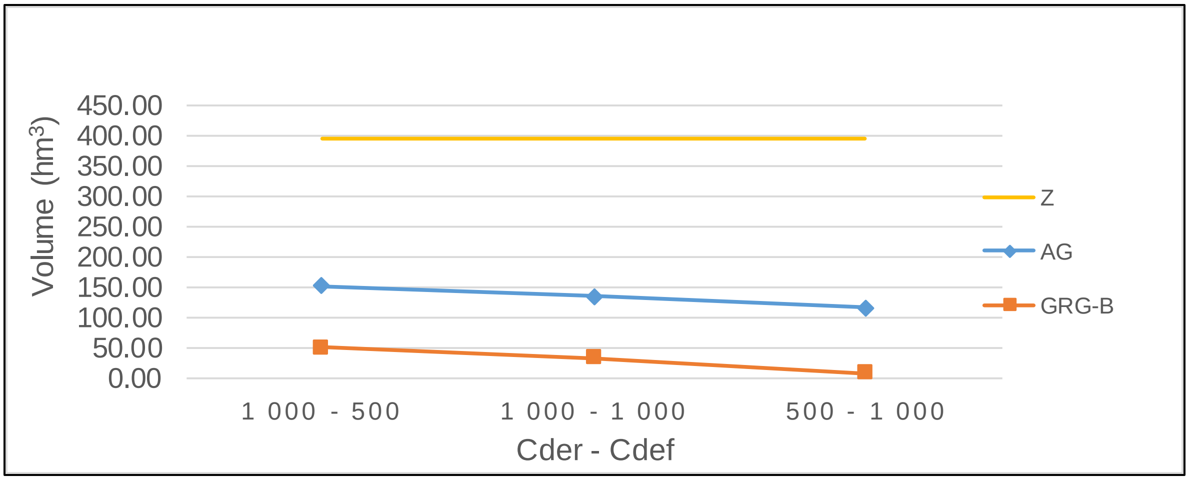

Figure 17. Comparison of total deficits 1940-2016.

From the previous graphs, it can be seen that when comparing the total spills of the tests made with the historical Z curve, GRG, and GA, the results of GRG and GA are very similar and that both policies are better in terms of deficit and total spills than those obtained with the historical Z curve. However, when comparing the deficits, it is found that in the GRG simulations they are of lesser magnitude. Spilled and deficit volumes were also accounted for. Table 6 presents the number of months in which these events occurred in each simulation. It can be observed again that the number of deficits is lower in the GRG simulations. Regarding spills, the results are very similar to both optimization methods. On the other hand, the results of the simulations carried out from the operation rules, obtained with the two optimization methods, compared with the historical operation (Z in Table 6) show fewer months with spills and, above all, fewer months with deficits.

Table 6. The number of months with spills and deficits produced by simulations.

Simulation	Spill	Deficit
Z	37	61
GA-1	25	40
GA-2	29	36
GA-3	33	31
GRG-B1	18	23
GRG-B2	25	16
GRG-B3	33	6

To have greater detail on the monthly behavior of the spills and deficits obtained with the historical Z curve (indicated as Z) and those optimized, the policies GRG-B3 and GA-3 were selected from Table 6 as they have the lowest total volumes of deficits and a smaller number of those events occurred monthly during the simulations. As seen in Figure 18 and Figure 19.

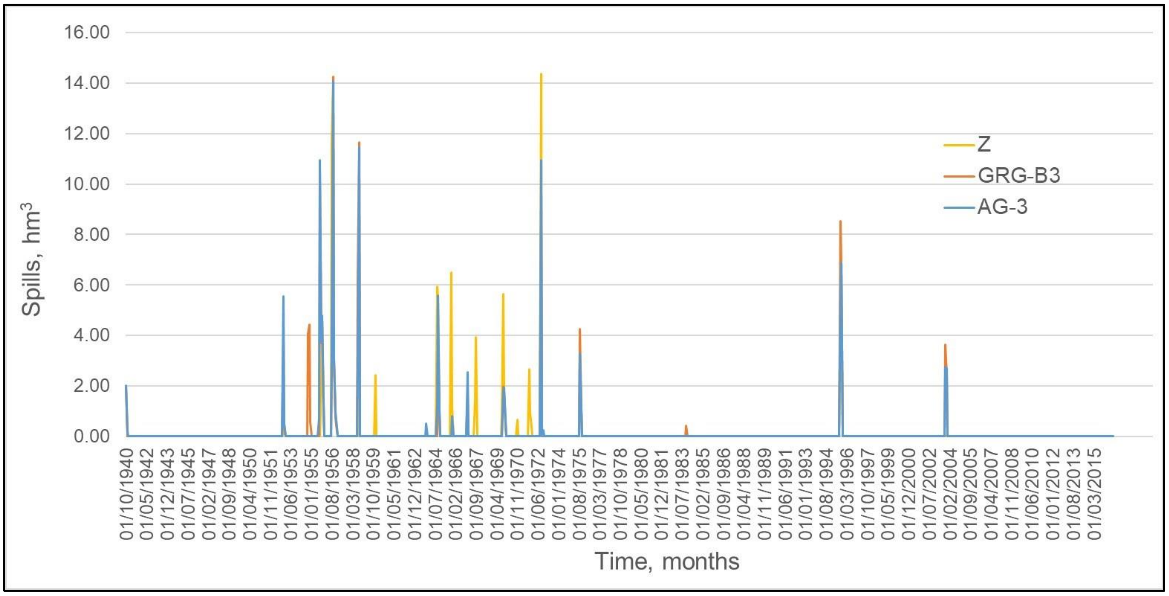

Figure 18. Monthly spills 1940-2016.

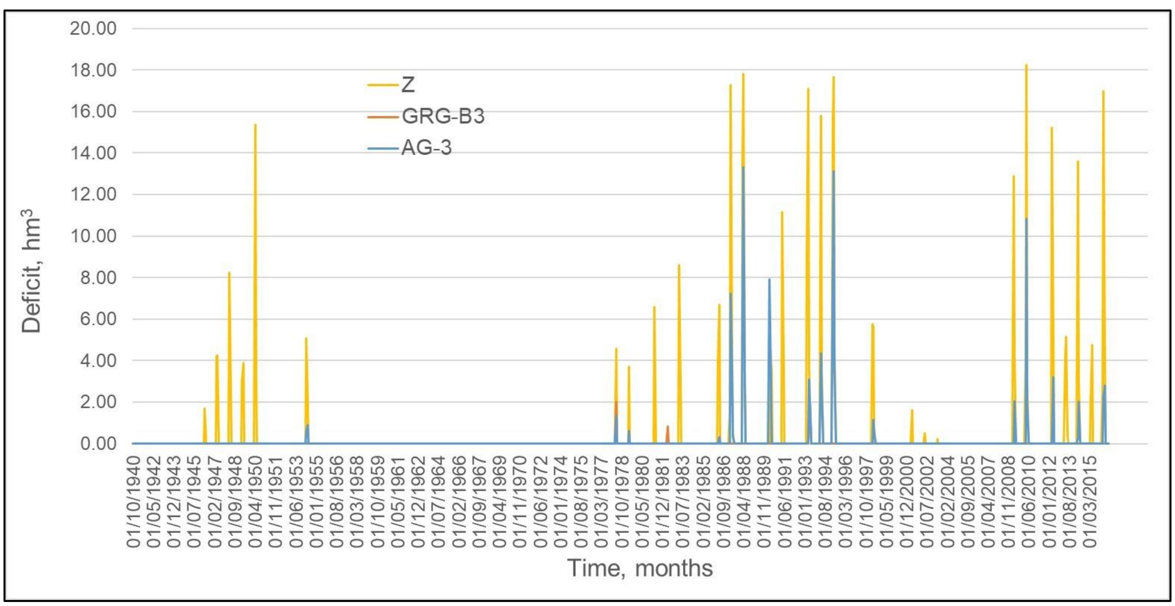

Figure 19. Monthly deficits 1940-2016.

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As the GRG method can give a local optimum and given the small difference between the GRG-B3 and GA-3 policies in the number of times a spill or deficit may occur, it was decided that GA-3 was the best policy to simulate 10 synthetic series of 100 years each. An addition of almost 20 more years to the historical data was considered to deepen the analysis of long-term behavior. Table 7 shows the average values of the volumes of water extracted for irrigation and domestic water, and spilled and missing, given in the simulations using the 10 synthetic series. Table 8 shows the annual average volumes of the simulations with the historical record and with the synthetic series, calculated as the quotient of the values in Table 7 between the simulated years: 77 for the historical record and 100 for the synthetic series. From Table 7, it can be seen that in general, the deficit volumes were smaller when using the synthetic values, while the spilled volumes were greater.

Table 7. Summary of reservoir operation simulations using the historical record and synthetic series.

	Irrig Ext.	**Domestic Ext.**	**Spill**	**Def**
Simulation	**(hm^3)**			
Z Historical	3 585.08	1 631.94	124.60	493.45
GA-3 with Hist. Record	3 289.47	1 602.46	116.41	116.05

GS-3 SS Average	4 101.68	2 081.12	215.02	64.28

Table 8. Summary of the annual average volumes of reservoir operation simulations using the historical record and synthetic series, under different operating policies.

	Irrig Ext.	**Domestic Ext.**	**Spill**	**Def**
Simulation	**(hm^3)**			
Z Historical	45.38	20.65	1.57	6.24
GA-3 R. with Hist. Record	42.72	20.81	1.51	1.51
GA-3 SS Average	41.02	20.81	2.15	0.64

Conclusions

Using the GRG algorithm to obtain optimal operating policies for irrigation and drinking water purposes has multiple advantages, especially its ease of use and the speed with which results are found, as long as the number of iterations is not too many. However, the GRG algorithm does not always converge to a global optimum, so it is advisable to use more robust methods.

On the other hand, the simulations made with the GA algorithm converge to global optimums for each simulation, because the process does not start from any predefined value for the Z curve, but rather from different values randomly generated, that are tested. The response given by the GA for a proposal of penalty coefficients was invariant.

The Svanidze method applied to the runoff from each basin was able to reproduce the behavior pattern of the mean statistics, standard deviation, and coefficient of variation in all months, except in April for the coefficient of variation. Although the behavior of the coefficient of skewness could not be reproduced exactly, the values preserve the historical trend.

Since the reservoir of the Cointzio dam supplies water for irrigation of the DR-020, greater importance can be given to reducing the deficit, as long as the maximum monthly spills do not have a potentially devastating effect. In this work, the policy obtained in the G3-3 simulation is recommended. This keeps the spill and deficit volumes balanced, but without reaching extreme values and keeping the spill and deficit volumes as similar as possible. In the long term, when simulating the behavior of the system with this policy with the 10 series of 100 years obtained with the Svanidze method, the average annual volume of spill increases slightly, from 1.51 to 2.15 hm^3, but the average annual deficit is reduced

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from 1.51 to only 0.64 hm^3, thus guaranteeing the supply of water for Irrigation District 020 and domestic water for the City of Morelia.

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