Operation of Dokan Reservoir under Stochastic Conditions as Regards the Inflows and the Energy Demands

G I Rashed
School of Electrical Engineering, Wuhan University
No.8 East Lake South Road, Wuhan, Hubei, 430072, China

Abstract. This paper presented a way of obtaining certain operating rules on time steps for the management of a large reservoir operation with a peak hydropower plant associated to it. The rules were allowed to have the form of non-linear regression equations which link a decision variable (here the water volume in the reservoir at the end of the time step) by several parameters influencing it.

This paper considered the Dokan hydroelectric development KR-Iraq, which operation data are available for. It was showing that both the monthly average inflows and the monthly power demands are random variables. A model of deterministic dynamic programming intending the minimization of the total amount of the squares differences between the demanded energy and the generated energy is run with a multitude of annual scenarios of inflows and monthly required energies.

The operating rules achieved allow the efficient and safe management of the operation and it is quietly and accurately known the forecast of the inflow and of the energy demand on the next time step.

1. Introduction
A model of stochastic dynamic programming for the optimization of a large reservoir operation, with a peak hydropower plant associated was presented in this paper. It was showed that the frequency distributions for the average inflows from each month of the year, and the model provides the matrix of the most appropriate volumes for the reservoir at the end of each month depending on the reservoir volumes at the beginning of the month. There were considered two variants of objective function, namely: maximization of the energy potential average quantity achieved and maximization of the potential mean value of the absolute deviations between the monthly outflows and the multiannual average inflow. Dokan hydroelectric development was used as application, and the operation simulation program (based on the results of the stochastic optimization model) was run with data recorded during October 1978 – September 2000, supplying very promising data.

Optimal operation of reservoirs for electric generation was presented in [1]. It reports several tests carried out on a simple system under special conditions highlighting some important characteristics of their optimal behavior. A non-linear multiobjective optimization model is developed in [2] to obtain optimal annual scheduling for control of power generation in serial or parallel hydropower plants. A review of ISO methods using data mining was presented in [3], after briefly introduce the conventional techniques and their limitations, new techniques of data mining such as genetic algorithms, neural networks, decision tree, and particle swarm optimization are described in detail.

The rest of this paper is organized as follows, In the next section, we present deterministic dynamic programming (DP) model, the Obtaining of data required by the operating rule introduced in section 3,
Genetic algorithm for the operating rules coefficients are presented in section 4, and in section 5 present the research conclusions.

2. Deterministic dynamic programming (DP) model

Proposed DP model had in view the performance function:

$$
\min \left\{ F = \sum_{k=1}^{K} (E_k^* - E_k)^2 \right\},
$$

where $k$ is the number of time steps over the annual analysis horizon, $E_k^*$ is the demanded energy and $E_k$ is the energy generated within step $k$.

As decision variables there were considered the water volume in the reservoir at the end of time step $k$, $V_k^f$, and as state variables the water volume in the reservoir at the beginning of the time step $k$, $V_k^i$.

Balance equation was accepted under its simple form:

$$
V_k^i = V_k^f + A_k - D_k
$$

Where $A_k$ is the inflow stock, $D_k$ is the outflow stock on step $k$, whereas other inputs and losses are disregarded.

Operation shall comply with the following restrictions, as well:

$$
V_k^{\text{min}} \leq V_k^f \leq V_k^{\text{max}} \quad \text{for} \quad k = 1, 2, \ldots, K
$$

and,

$$
D_k^{\text{min}} \leq D_k \leq c_k \cdot D_k^{\text{max}} \quad \text{for} \quad k = 1, 2, \ldots, K
$$

$V_k^{\text{max}}$ was the maximum volume allowed in the reservoir at the end of the step $k$, $V_k^{\text{min}}$ is the minimum volume allowed in the reservoir, $D_k^{\text{min}}$ is the minimum outflow stock needed for the downstream users, $D_k^{\text{max}}$ is the outflow stock corresponding to the maximum flow of the turbine by the hydropower plant, and $c_k$ is the availability coefficient of this flow on step $k$.

Power output achieved within the time step $k$ is given by the relation:

$$
E_k = e(V_k^i \cdot D_k) \quad \text{if} \quad D_k \leq c_k \cdot D_k^{\text{max}}
$$

or

$$
E_k = e(V_k^i) \cdot c_k \cdot D_k^{\text{max}} \quad \text{if} \quad D_k \leq c_k \cdot D_k^{\text{max}}
$$

where $e(V_k^i)$ is the specific power output (GWh/1 mil. m$^3$) depending on the average volume

$$
\bar{V}_k = \frac{1}{2} (V_k^i + V_k^f)
$$

For the application at Dokan hydroelectric development it was used the following relation:

$$
e(\bar{z}_k) = 0.00023 \times (\bar{z}_k - 415)
$$

and the connection between the $\bar{V}_k$ and the elevation of the free surface, $\bar{z}_k$ is found by using the reservoir capacity curve $V = f(z)$ which is already known.

For a set of specified inflow values $A_k$, $k = 1, 2, \ldots, K$, and of the demanded energy, respectively, $E_k^*$, $k = 1, 2, \ldots, K$, the DP model provides on each time step $k$, the optimal values of the final volume and generated energy depending on the water volume in the reservoir at the beginning of the time step. For solving the model in case of Dokan reservoir, it was used a discretization step $\Delta V = 200$ mil. m$^3$, the $\min(V_k^{\text{min}})$ and $\max(V_k^{\text{max}})$ values were required at 1400 mil. m$^3$ (corresponding to the free surface
elevation of about 508.1 mASL) such as the above-mentioned optimal values are found for about \((6000 – 1400)/200 = 23\) values of the reservoir initial volume, in each time step. Explicitly, for simplifying the presentation of the application for Dokan case, there were allowed bimonthly time steps over the hydrological year (1 October – 30 September). For the control of potential flood to be allowed, the maximum volumes allowed in the reservoir, \(V^\text{max}_k\) were required to be of 5700, 5700, 5600, 5600, 5800 and 6000 mil. m\(^3\), respectively (considering the hydrological regime features). Minimum volumes allowed, \(V^\text{min}_k\) were of 2500, 2000, 1800, 1400, 3400 and 3000 mil. m\(^3\), respectively and they were determined the high water periods or the period with higher energy demand. 5 \times 94 = 470 m\(^3\).s\(^{-1}\) was considered as turbine discharge, being remarked that the discharge on unit of 94 m\(^3\).s\(^{-1}\) can be discharged within the whole reasonable head range. The availability coefficients of the discharge were taken to be similar for all the time steps, having the value of \(c_k = 0.9\) for \(k = 1, 2, \ldots, 6\). Minimum flow needed by the downstream users was chosen to be of 20 m\(^3\).s\(^{-1}\) and it was accepted to be the same for all the time steps.

3. Obtaining of data required by the operating rule

Regarding the scenarios of inflows in Dokan reservoir, there were used the available data recorded during October 1966 – September 2000, meaning 35 years known from studies or from operation. These data were grouped on 6 bimonthly periods for each hydrological year and they are shown in Table 1.

Table 1. Bimonthly average flows in Dokan reservoir during October 1966 – September 2000

|     | 1   | 2   | 3   | 4   | 5   | 6   | Mean |
|-----|-----|-----|-----|-----|-----|-----|------|
| 1   | 91.0| 101.0| 253.5| 233.5| 75.5| 84.5| 139.8|
| 2   | 89.5| 122.0| 317.0| 363.0| 115.0| 88.0| 182.0|
| 3   | 102.0| 178.5| 278.5| 478.5| 76.5| 85.0| 199.8|
| 4   | 94.0| 438.0| 925.5| 1001.5| 239.5| 171.0| 478.3|
| 5   | 138.5| 196.0| 242.5| 213.0| 117.5| 78.5| 164.3|
| 6   | 56.5| 67.5| 161.0| 439.0| 84.5| 69.0| 146.1|
| 7   | 75.5| 138.5| 372.5| 734.0| 160.5| 103.0| 264.0|
| 8   | 138.5| 110.5| 365.0| 293.5| 99.0| 73.0| 179.9|
| 9   | 77.0| 116.5| 818.0| 603.0| 235.0| 86.5| 322.7|
| 10  | 81.0| 128.0| 354.5| 268.0| 91.5| 64.0| 164.5|
| 11  | 67.0| 176.0| 353.0| 561.5| 138.0| 75.5| 228.5|
| 12  | 96.5| 125.0| 308.0| 328.0| 83.0| 101.5| 173.7|
| 13  | 102.0| 194.5| 360.0| 214.0| 162.0| 77.0| 184.9|
| 14  | 64.5| 268.5| 250.0| 209.0| 57.5| 51.5| 150.2|
| 15  | 51.0| 117.0| 304.5| 369.5| 80.0| 57.5| 163.3|
| 16  | 84.0| 137.5| 397.5| 346.0| 117.5| 72.0| 192.4|
| 17  | 84.5| 153.5| 377.5| 492.0| 112.0| 89.0| 218.1|
| 18  | 152.5| 155.0| 325.0| 303.0| 107.0| 68.0| 185.1|
| 19  | 62.5| 83.0| 133.0| 201.5| 56.0| 42.5| 96.4|
| 20  | 104.0| 240.5| 631.5| 470.5| 142.0| 74.5| 277.2|
| 21  | 86.5| 145.0| 260.0| 281.0| 89.5| 45.0| 151.2|
| 22  | 104.0| 155.5| 392.5| 353.5| 98.5| 54.5| 193.1|
| 23  | 92.5| 509.0| 1032.0| 664.5| 209.0| 87.5| 432.4|
| 24  | 92.0| 141.0| 222.0| 164.0| 48.5| 45.0| 118.8|
| 25  | 79.0| 224.5| 296.0| 282.5| 79.0| 35.5| 166.1|
| 26  | 62.0| 62.0| 348.0| 323.0| 62.5| 52.0| 151.6|
| 27  | 78.5| 330.0| 616.5| 927.5| 260.0| 75.5| 381.3|
| 28  | 123.0| 306.0| 382.0| 632.5| 181.5| 67.5| 381.3|
| 29  | 208.0| 389.0| 474.5| 365.5| 91.5| 57.5| 264.3|
| 30  | 196.5| 351.5| 415.0| 572.0| 138.0| 53.5| 287.8|
| 31  | 66.0| 105.5| 297.0| 352.0| 39.5| 36.0| 149.3|
| 32  | 41.5| 99.0| 290.5| 407.0| 104.5| 38.5| 163.5|
| 33  | 93.0| 198.5| 594.0| 479.0| 80.0| 33.0| 246.3|
| 34  | 51.0| 75.0| 147.0| 88.0| 24.0| 12.0| 66.2|
| 35  | 19.5| 73.5| 135.5| 125.0| 23.5| 12.5| 64.9|
As determined from the table, during the considered period, there were diverse annual hydrological regimes, with annual average inflows higher than the turbine capacity accepted in the PD model but also with inflow values below the turbine discharge on a single unit from the hydropower plant. During the high water season \((k = 3,4)\) there were years with inflows higher than twice of the turbine capacity considered in the DP model, and during the low waters periods there are bimonthly events when the inflow is lower even than the minimum flow of 20 \(\text{m}^3\text{s}^{-1}\) needed by the downstream users.

Thus, it can be stated that under the diversity of hydrological conditions these inflow data are quite representative.

As regards of the monthly power outputs, the available data recorded between March 1978 and December 2001 (excepting year 1994 when these are missing). Analyzing these data it was determined that the bimonthly power outputs recorded, on time steps, were included between: 28.4 – 312.2; 19.5 – 263.7; 23.8 – 285.8; 22.3 – 273.1; 56.1 – 401.6 and 68.3 – 486 GWh / 2 months, respectively. Consequently, the following are considered as reasonable ranges for the energy demand on time steps: 25 – 300; 20 – 280; 20 – 300; 20 – 300; 50 - 420 and 65 – 500 GWh/2 months, respectively.

By means of these limits for each bimonthly interval, time step, there were generated by random 35 annual sequences of 6 energy values on each time step, allowed as being demanded and planned.

Table 2 shows these probabilistic scenarios of energy annual demands from the system. There can be noticed that great variety of annual energy demands, from about 790 GWh up to over 1550 GWh.

**Table 2.** Bimonthly power demands from Dokan, hydroelectric development, synthetically generated

| 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|------|
| 1 | 291.0 | 259.0 | 150.0 | 184.0 | 206.0 | 121.0 | 1211.0 |
| 2 | 46.0 | 160.0 | 103.0 | 21.0 | 267.0 | 372.0 | 969.0 |
| 3 | 120.0 | 104.0 | 247.0 | 100.0 | 210.0 | 163.0 | 944.0 |
| 4 | 168.0 | 39.0 | 297.0 | 276.0 | 298.0 | 71.0 | 1149.0 |
| 5 | 25.0 | 100.0 | 213.0 | 136.0 | 346.0 | 146.0 | 966.0 |
| 6 | 294.0 | 103.0 | 125.0 | 28.0 | 366.0 | 211.0 | 1127.0 |
| 7 | 180.0 | 155.0 | 261.0 | 284.0 | 187.0 | 423.0 | 1490.0 |
| 8 | 253.0 | 226.0 | 233.0 | 125.0 | 72.0 | 145.0 | 1054.0 |
| 9 | 150.0 | 277.0 | 131.0 | 51.0 | 174.0 | 477.0 | 1260.0 |
| 10 | 149.0 | 183.0 | 174.0 | 110.0 | 288.0 | 417.0 | 1321.0 |
| 11 | 169.0 | 41.0 | 71.0 | 172.0 | 81.0 | 300.0 | 834.0 |
| 12 | 322.0 | 47.0 | 39.0 | 69.0 | 239.0 | 476.0 | 1192.0 |
| 13 | 297.0 | 84.0 | 112.0 | 45.0 | 186.0 | 120.0 | 844.0 |
| 14 | 311.0 | 131.0 | 294.0 | 215.0 | 182.0 | 268.0 | 1401.0 |
| 15 | 292.0 | 210.0 | 193.0 | 68.0 | 98.0 | 456.0 | 1317.0 |
| 16 | 187.0 | 188.0 | 155.0 | 179.0 | 234.0 | 72.0 | 1015.0 |
| 17 | 216.0 | 177.0 | 99.0 | 142.0 | 77.0 | 386.0 | 1097.0 |
| 18 | 223.0 | 48.0 | 119.0 | 29.0 | 330.0 | 264.0 | 1013.0 |
| 19 | 180.0 | 42.0 | 236.0 | 123.0 | 385.0 | 411.0 | 1377.0 |
| 20 | 292.0 | 91.0 | 92.0 | 294.0 | 296.0 | 88.0 | 1153.0 |
| 21 | 32.0 | 149.0 | 126.0 | 287.0 | 302.0 | 264.0 | 1160.0 |
| 22 | 151.0 | 68.0 | 278.0 | 48.0 | 344.0 | 170.0 | 1059.0 |
| 23 | 30.0 | 24.0 | 288.0 | 155.0 | 183.0 | 218.0 | 898 |
| 24 | 307.0 | 33.0 | 183.0 | 128.0 | 127.0 | 298.0 | 1076.0 |
| 25 | 76.0 | 105.0 | 87.0 | 93.0 | 400.0 | 168.0 | 929.0 |
| 26 | 201.0 | 202.0 | 27.0 | 236.0 | 237.0 | 218.0 | 1121.0 |
| 27 | 241.0 | 215.0 | 300.0 | 201.0 | 359.0 | 195.0 | 1511.0 |
| 28 | 111.0 | 84.0 | 63.0 | 239.0 | 164.0 | 130.0 | 791.0 |
| 29 | 136.0 | 65.0 | 117.0 | 178.0 | 60.0 | 268.0 | 824.0 |
| 30 | 169.0 | 222.0 | 50.0 | 29.0 | 279.0 | 422.0 | 1171.0 |
| 31 | 33.0 | 136.0 | 211.0 | 126.0 | 249.0 | 234.0 | 989.0 |
| 32 | 306.0 | 254.0 | 62.0 | 124.0 | 337.0 | 86.0 | 1169.0 |
| 33 | 220.0 | 55.0 | 203.0 | 213.0 | 194.0 | 250.0 | 1135.0 |
| 34 | 310.0 | 23.0 | 46.0 | 265.0 | 246.0 | 76.0 | 966.0 |
| 35 | 280.0 | 78.0 | 116.0 | 274.0 | 395.0 | 412.0 | 1555.0 |
At the multiannual level it is noticed that a demand of about 1117 GWh/year, this value close of the one found in [4]. Being available the 35 annual sequences of inflows recorded and the 35 annual energy sequences demanded from Dokan hydroelectric development (synthetically generated, but based on data known from operation), the 1225 various scenarios of inflows power demands were likely to be allowed.

For each of these scenarios it was run the DP model described in section II, meaning that the first year with the 6 bimonthly average flows, with each of the 35 annual scenarios of demanded bimonthly energies; the second year with the 6 bimonthly average flows, with each of the 35 annual scenarios of demanded bimonthly energies, and so on.

Therefore, a number of “lessons” resulted for each time step $k$, consisting in:

$$L_n = \{V'_n(n), A(n), E(n), V_f(n)\} \quad n = 1,2,\ldots,N$$

where $n$ is the “lesson” number; $V'_n(n)$ is the water volume in the reservoir at the beginning of the step $k$ for “lesson” $n$; $A(n)$ is the inflow on step $k$, from “lesson” $n$; $E(n)$ is the energy generated on step $k$, “lesson” $n$, and $V_f(n)$ is the most appropriate volume for the reservoir at the end of step $k$, from “lesson” $n$ (according to DP model and hydrological energetic conditions from year and step $k$).

After some redundant “lessons” have been removed (with similar values of the four concern parameters), there resulted on bimonthly seasons a number $N$ of: 13 966; 15 257; 17 040; 17 255; 13 040 and 11 232 “lessons”, respectively, to be used in order to find the coefficients $x_i$, $i = 1,7$ from the bimonthly operating rules.

Just as an example, table 3 shows some of the “lessons” for the first bimonthly time step (October – November).

| A (m³.s⁻¹) | E (GWh) | V₁ (mil. m³) |
|-----------|---------|--------------|
| 56.5      | 30      | 3000 3400 3800 4200 4600 5000 5400 5800 |
|           | 30      | 3000 3400 3800 4200 4600 5000 5200 5600 |
|           | 187     | 2600 2800 3200 3600 4000 4400 4800 5000 |
|           | 307     | 2600 2600 2600 2800 3200 3800 4000 4400 |
| 91        | 30      | 3200 3600 4000 4400 4800 5200 5400 5800 |
|           | 187     | 2800 3200 3400 3800 4200 4600 5000 5400 |
|           | 307     | 2600 2600 2600 2800 3000 3400 4000 4400 |
| 196.5     | 30      | 3000 3200 3600 3800 4000 4400 4600 4800 |
|           | 187     | 2600 2800 3000 3400 3600 4000 4400 4800 |
|           | 307     | 2600 2600 2600 2800 3200 3600 4000 4400 |

Even from these few examples it can be remarked the diversity of situations the data consist in. For instance, at a reduced inflow of 56.5 m³.s⁻¹ and demanded energy on the first step of only 30 GWH, the final optimal volumes are similar to the initial ones (first 6 values) or reduced only with 200 mil.m³. Instead of this, for a very high inflow of 196.5 m³.s⁻¹ and for a similar energy demand of 30 GWh, the optimal final volumes are constantly lower than the initial ones. Differences are explained by means of the hydrological regime and energy demands from the other 5 time steps of the years.

4. Genetic algorithm for the operating rules coefficients

A genetic algorithm (GA) adapted to the problem was used in order to find the coefficients $x_i$, $i = 1,7$ from the following relations.

$$V_f = x_1 + x_2 \cdot V'_n + x_3 \cdot A + x_4 \cdot E$$

(9)
where $V_f$ is the water volume in the reservoir at the end of the time step, $V_i$ is the water volume in the reservoir at the beginning of the time step, and $A$ and $E$ are the inflow and the energy demanded on the time step.

Coefficients $x_1, x_2, \ldots, x_7$ for each time step are resulted by a genetic algorithm which processes the results of the scenarios run by the DP model.

$N$ is the number of “lessons” available for a certain time step.

An individual chromosome (a solution) from GA is represented by a set of concrete numerical values for the genes (unknowns) $x_i, i = 1, 7$.

In order to enable the establishing of certain variation in possible ranges of each unknown, it is recommendable for the “cause” and “effect” parameters to be normalized on the range [0;1]. For the initial and final volume, the normalization was carried out by dividing it to $V_{\text{max}} = 6,800$ mil.m$^3$ (volume at NWL). The inflow was normalized as compared to the value of 1100 m$^3$.s$^{-1}$ (higher than the maximum flow from the last line of table I) and the demanded energy was normalized by being divided to 500 GWh (higher than the maximum value from the last line of table II).

This way, it becomes reasonable for the multiplicative coefficients $x_1, x_2, x_3$ and $x_4$ to be searched for within the range [-1;1], and the exponential coefficients $x_5, x_6$ and $x_7$ within a range established between 0 (not depending on the said parameter) and a reasonable upper limit of 3 or 5.

Coding of the individual was carried out by real number, thus the genes being able to take any real values from the specified ranges. Performance function of a certain solution $x_i, i = 1, 7$ can be defined by one of the following relations:

\[
\begin{align*}
    f_1(x) &= \frac{1}{N} \sum_{n=1}^{N} \left[ V_f(n) - V_f^*(x) \right]^2 \\
    f_2(x) &= \frac{1}{N} \sum_{n=1}^{N} \left| V_f(n) - V_f^*(x) \right| \\
    f_3(x) &= \max_{n=1}^{N} \left[ V_f(n) - V_f^*(x) \right] \\
    f_4(x) &= \max_{n=1}^{N} \left[ V_f(n) - V_f^*(x) \right]^2
\end{align*}
\]

(10)

where $V_f^*(x)$ represents the calculated value of $V_f$ for a set of values $x_i, i = 1, 7$ and values $V_i, A, E$ from the “lesson” $n$, and $V_f^*(n)$ is the optimal decision from “lesson” $n$.

Form $f_1$ aims the minimization of the square mean deviation, $f_2$ - minimization of the absolute mean deviation, $f_3$ - minimization of the maximum absolute, and $f_4$ - minimization of the square maximum deviation.

Assessment value of the individual was selected to be as follows:

\[
E_v(x) = \frac{S - f(x)}{S}
\]

(11)

Where $S$ is the highest value of $f$ given by (10), out of all the individuals and all the generations up to the current one, inclusively. In this way any selection procedure shall select individuals of high $E_v$ values, which determines low values of $f(x)$. Certainly, for $f(x) = 0$, it results $E_v(x) = 1$ – maximum value likely to be achieved within the past generations and with the individuals tested from each population.

It was worked with populations of $m = 90$ each individuals and there were produced $T = 1000$ generations, in 3 running’s for each time step $k = 1, 6$.
As a selection procedure it was used the selection by normalized geometrical ordination where there is considered the row of decreasing ordered chromosomes according to values $E_v(x)$, the first being the most performing from the generation. Individual probabilities of selection for the ordered individuals were achieved by relation

$$p_i = \frac{a(1-a)^{i-1}}{1-(1-a)^m} \quad i = 1,2,\ldots,m$$

with $m = 90$ (population size); $a = 0.08$ and $i$ equal to the rank in the ordered row. Cumulated probabilities up to rank $i$ shall be:

$$q_i = \sum_{j=1}^{i} p_i$$

and for the selection it is generated a random number $r \in [0;1]$ and the first chromosome $i$ to which $q_i \geq r$ passes to the genetic basis for the formation of the next generation.

As genetic operators there were used the arithmetic crossing applied with the probability $p_c = 0.75$ and the irregular mutation of probability $p_m = 0.03$.

For the simple arithmetic crossing, two “parents” solutions $p_1$ and $p_2$ generate two “children” solutions, $c_1$ and $c_2$, according to the scheme:

$$c_1 = r \cdot p_1 + (1-r) \cdot p_2; \quad c_2 = (1-r) \cdot p_1 + r \cdot p_2$$

with $r$ generated by random from the range $r \in [0;1]$.

In the irregular mutation, if at the chromosome $x$ it was selected for mutation $x_k$ gene, then it is transformed in $x'_k$ according to the scheme:

$$x'_k = \begin{cases} x_k + (x'_k - x_k) \cdot \delta & \text{if } r_1 < 0.5 \\ x_k - (x'_k - x_k) \cdot \delta & \text{if } r_1 \geq 0.5 \end{cases}$$

where $\delta = r_2 \cdot (1 - t / T)^b$, with $r_1$ and $r_2$, two random numbers from [0;1] range; $t$ is current generation; $T$ is the total number of generations (required for running’s at 1000); $x'_k$ and $x_k$ the left and right limits of the range allowed for $x_k$, and $b$ is a parameter taken as $b = 1.75$.

GA program was run by similar procedures, operators and values of the parameters for each time step, 3 times each. To serve as example, table 4 includes the important results of the 3 running’s for the bimonthly step $K = 6$ (August – September) and $f_l$ form from (10).

Table 4. Results for the operating rule on step $K = 6$

| Running | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $f$ | $E_v$ |
|---------|-------|-------|-------|-------|-------|-------|-------|-----|------|
| 1       | 0.510 | 0.5801| 0.8089| -0.275| 3.272 | 1.116 | 0.774 | 0.001| 0.999|
| 2       | 0.355 | 0.6362| 0.9205| -0.282| 1.619 | 1.182 | 0.734 | 0.001| 0.999|
| 3       | 0.638 | 0.5926| 0.9320| -0.370| 3.727 | 1.221 | 0.463 | 0.001| 0.999|

From the 3 running’s for each $k = 1,2,\ldots,6$, it was selected as solution for the seasonal operating rule the one having the minimum value $f$ (in table IV, running solution 3).

Table 5 shows the optimal values of coefficients $x_i$, $i = 1,7$ for all the 6 bimonthly time steps and form $f_l$ of the performance function from (11).
Table. 5 Coefficients of the operating rules on time steps for $f_1$ form from (10)

| Time step | $x_1$    | $x_2$    | $x_3$    | $x_4$    | $x_5$    | $x_6$    | $x_7$    |
|-----------|----------|----------|----------|----------|----------|----------|----------|
| 1         | 0.39528  | 0.57371  | -0.78941 | -0.23741 | 2.09749  | 4.38639  | 0.99809  |
| 2         | 0.31030  | 0.64725  | 0.98785  | -0.29381 | 1.58781  | 2.31995  | 1.38644  |
| 3         | 0.34501  | 0.62280  | 0.42216  | -0.18682 | 1.25778  | 1.76063  | 0.95754  |
| 4         | 0.43470  | 0.60262  | 0.48224  | -0.22504 | 1.21564  | 1.14401  | 0.23711  |
| 5         | 0.49046  | 0.52321  | 0.47776  | -0.22161 | 2.73456  | 0.97114  | 0.97078  |
| 6         | 0.63823  | 0.59266  | 0.93204  | -0.37091 | 3.72771  | 1.22192  | 0.46372  |

Fig. 1 shows the variation of the water volume in the reservoir during the 23 simulation years

5. Conclusions

This paper presented a way of obtaining certain operating rules on time steps for the management of a large reservoir operation, with a peak hydropower plant associated to it.

The rules are allowed to have the form of non-linear regression equations which link a decision variable (here the water volume in the reservoir at the end of the time step) by several parameters influencing it (here the water volume in the reservoir at the beginning of the time step, the inflow and the energy demanded on the time step).

These “lessons” were found by means of a deterministic dynamic programming model for the optimization of the hydroelectric development annual operation. The respective model intends the minimization of the sum, on time steps, of the square deviations between the demanded energy and the generated one.

Optimization model has run with 35 annual scenarios of reservoir inflows (known from records) and 35 annual scenarios of energy demands (synthetically generated from the operation known ranges), respectively, meaning a total of $35 \times 35 = 1225$ different scenarios of inflows demanded energies.

Operating rules found were checked by means of the operation simulation model running on 23 consecutive years. Only in about 2% of the time steps of this period, the solution provided by the operating rules could not be adjusted, being required overflowing (which were unavoidable also in the real operation due to the extremely high inflows).

The annual average energy generated during the verification period resulted to be with over 4.5% higher than the required one.

It can be stated that the operating rules achieved allow the efficient and safe management of the operation; it is accurately known the forecast of the inflow and of the energy demand on the next time step.
References

[1] S. Soares, A.A.F.M. Carneiro. Optimal Operation of Reservoirs for Electric Generation, IEEE Transactions on Power Delivery, 6(3)(1991),1101-1107.

[2] S. Ali A Moosavian, A. Ghafari, A. Salimi and N. Abdi, Non-Linear Multiobjective Optimization for Control of Hydropower Plants Network, Proceedings of the 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, (2008) 1278-1283.

[3] Xue Zhen Li, Li Zhong Xu, and Yang Guo Chen. Implicit Stochastic Optimization With Data Mining For Reservoir System Operation. Proceeding of Ninth International Conference on Machine Learning and Cybernetics, Qingdao, China, (2010) 2410-2415.

[4] Khalid Ahmed Rashid., Optimal operation of major hydropower plants; PhD Thesis, Univ. Politehnica of Bucharest, 2005.